



RESEARCH AT GANIL A COMPILATION 1996-1997

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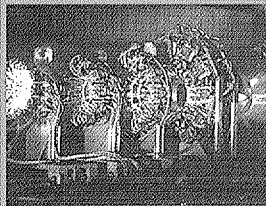
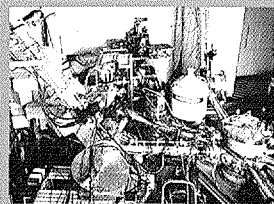
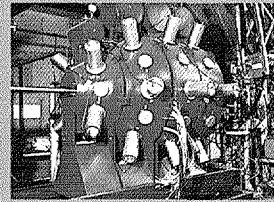
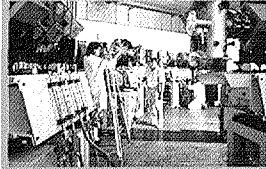
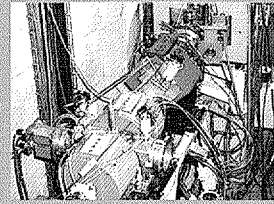
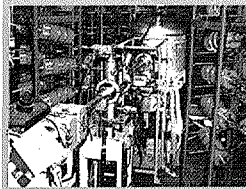
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1996-1997

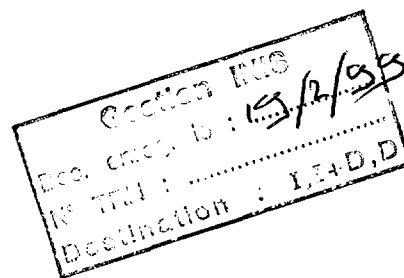
A COMPILATION

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RESEARCH AT GANIL

A COMPILATION

1996 - 1997

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FOREWORD

The present compilation gives an overview of experimental results obtained with the GANIL facility during the period 1996-1997. For the first time, it includes nuclear physics activities as well as interdisciplinary research. The latter was previously published independently by the CIRIL laboratory which is acting as a host laboratory for this community.

The GANIL and the CIRIL laboratories agreed to present one single report in order to emphasize the broad scientific activity favored by the large variety of beams, energies and experimental equipments offered by the GANIL facility. Therefore the scientific domain ~~which is~~ presented here extends well beyond the traditional nuclear physics and includes atomic physics, condensed matter physics, nuclear astrophysics, radiation chemistry, radiobiology as well as applied physics.

In the nuclear physics field, many new results have been obtained during that period concerning nuclear structure as well as the dynamics of nuclear collisions, and

Further experiments have been performed with the INDRA device which should largely contribute to get a well detailed knowledge of the nuclear disassembly of complex systems. Results which are presented so far deal in particular with the problem of energy equilibration, timescales and the origin of multifragmentation.

Nuclear structure studies using both stable and radioactive beams have led to quite exciting results on the behaviour of exotic systems at the limits of stability. They deal with halo systems, study of shell closures far from stability, the existence of nuclear molecules as well as measurements of fundamental data as half lives, nuclear masses, nuclear radii, quadrupole and magnetic moments. In this domain, LISE and SPEG spectrometers have been heavily used.

Investigations of nuclear structure by means of nuclear reactions have also been performed, especially using SPEG and ORION devices.

Besides nuclear physics, activities have evolved towards an increased diversification. In addition to traditional fields of atomic and solid state physics, which remain very active, covering an even broader energetic domain through the use of ECR sources, new thematics such as radiation chemistry and radiobiology are progressively being tackled. Such promising is their development that the old denomination of " swift heavy ion physics " given to this field of activity happened to be more and more inappropriate and had to be replaced by the new one of " interdisciplinary research ".

With the forthcoming SPIRAL radioactive beam facility and the undergoing developments of new experimental lines (irradiation lines after the C0 injector) and devices (VAMOS spectrometer and EXOGAM detector), there is no doubt that a rich research programme is expected to be pursued in the future.

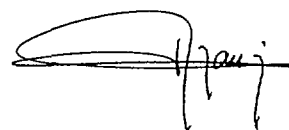
We are much indebted to the authors for the quality of their contributions.



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A-C) - NUCLEAR PHYSICS

A - NUCLEAR STRUCTURE

A1 - NUCLEAR SPECTROSCOPY

TWO-NEUTRON CORRELATIONS AT SMALL RELATIVE MOMENTA IN $^{86}\text{Kr} + ^{165}\text{Ho}$ AND $^{40}\text{Ar} + ^{197}\text{Au}$ REACTIONS AT 60 MeV/u

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Correlations between particles emitted with small relative velocities are widely used to study the space-time properties of the emission process in lepton, hadron and heavy-ion collisions[1]. Charged particle correlations are affected by the long range Coulomb forces from the emitting source or from other fragments of nuclear disintegration rendering ambiguous the interpretation of the results. Two-neutron correlations are free of it. Despite this favorable property the data on neutron-neutron correlations are very scarce. The cross-talk effects in the detection of neutrons in coincidence usually preclude the measurement of two-neutron correlation in the region of small relative momenta.

In the frame of the GANIL E236[2] and E240[3] experiments performed with the neutron detector DEMON, the two-neutron correlations were measured by looking at a cluster of 12 detectors installed at three different distances from the target. The cross-talk effects in the two-neutron correlations were eliminated using the combination of geometrical and kinematical relations[4]. The cluster for correlation measurements was placed at the mean angle about 50 degrees with respect to the beam axis.

The dependences of the experimental two-neutron correlation functions on k^* , half of momentum difference in the rest system of two-neutron pair, are presented in the Fig.1. The data are for two different reactions: $^{86}\text{Kr} + ^{165}\text{Ho}$ (E236 experiment) and $^{40}\text{Ar} + ^{197}\text{Au}$ (E240 experiment). The incident energy per nucleon, 60 MeV/u, was the same in both experiments and geometrical configurations of detectors were identical. The results are presented together for comparison.

The left hand part of the figure shows the correlation functions for neutrons with laboratory kinetic energies greater than 3MeV; the right hand part is for neutron energies greater than 10 MeV. In the first case the forms of correlation functions are the same for both reactions; in the second case, a clear difference appears. Note that higher correlation effect corresponds, in general, to smaller space-time intervals between the emission of particles.

The detected neutrons come from different sources and their origin can be related to the neutron energies. Low energies correspond predominately to the target fragmentation, mid-rapidity region is mostly populated by the promptly emitted particles from the compact system formed at the early stage of the collision, the highest energies can be attributed to the projectile disintegration.

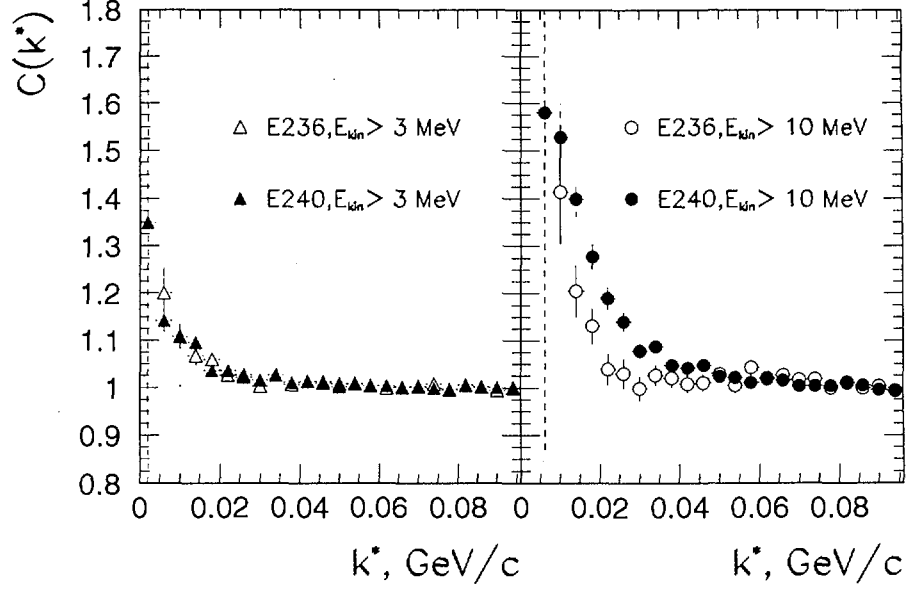


Fig.1 Neutron-neutron correlation functions for different reactions and different minimal neutron energies; see text for details.

The tendencies seen in the figures are in qualitative agreement with this expectation. Low energy neutrons seem to be emitted from the sources of similar space-time properties in both reactions. The prompt stage of the collision process shows different behavior in the space and time for the two reactions studied.

It should be noted here[1] that the form of correlation function is also very sensitive to the details of the reaction dynamics and thus, the two-particle correlations in the region of small relative velocities can be used as a tool to verify the validity of dynamical models. The works on comparison of the experimental data presented here with several dynamical descriptions are in progress.

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ELASTIC AND INELASTIC PROTON SCATTERING ON THE UNSTABLE ^{20}O NUCLEUS MEASURED WITH THE "MUST" DETECTOR ARRAY

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Abstract.

A 43 MeV/nucleon ^{20}O secondary beam obtained by using the SISSI solenoid at GANIL was scattered on a CH_2 target. The angle and energy of the recoiling protons were measured with the MUST Silicon-strip array yielding an excitation energy spectrum and angular distributions for elastic and inelastic proton scattering. For comparison, data was also measured for the ^{18}O stable isotope.

INTRODUCTION

The availability of radioactive nuclear beams with reasonable intensity and optical quality furnishes the tantalizing opportunity to study direct nuclear reactions, such as elastic and inelastic scattering and transfer reactions, induced by unstable nuclei on light particles. Such reactions are performed in inverse kinematics, where the radioactive nucleus of interest bombards a target containing the light particles. An efficient method to gain access to the excitation energy and scattering angle characterizing the reaction is to measure the energy and angle of the recoiling particle. Experiments of this type, concerning elastic and inelastic proton scattering, have already been performed at RIKEN [1] and the NSCL/MSU [2]. To perform such studies at GANIL, a silicon-strip array named MUST was recently constructed by the collaboration between IPN-Orsay, CEA Bruyères-le-Châtel and CEA Saclay. In the following we will report on the preliminary results obtained for the $^{20}\text{O}(\text{p},\text{p}')$ experiment performed at GANIL by using the MUST array.

EXPERIMENTAL SETUP AND PRELIMINARY RESULTS

A subject of current interest is the evolution of density and transition density distributions for nuclei far from stability. The measurement of the angular distributions of elastic and inelastic proton scattering allows us to test theoretical predictions of these quantities through microscopic folding model analyses. As a first experiment with the MUST detector, we have measured at GANIL $^{20}\text{O}(p,p')$ angular distributions of elastic scattering and inelastic scattering towards the first collective 2^+ and 3^- states. ^{18}O scattering was also measured for comparison. The secondary beams, produced by fragmentation of a 77 MeV/u ^{40}Ar beam and re-focused with the SISSI solenoid, impinged on a 2mg/cm² CH₂ target. The ^{20}O beam had an intensity of approximately 5×10^3 pps and was 98% pure. The energy of the secondary beam was 43 MeV/nucleon. The ^{18}O beam, also produced by fragmentation, had the same energy as ^{20}O and an intensity of 3×10^4 pps.

The angle and energy of recoiling protons were measured by the MUST array [3–5]. The array is composed of 8 telescopes consisting of 300 μm silicon strip detector with 60 vertical and 60 horizontal strips of 1 mm wide, backed by a 3 mm Si(Li) detector and a 15 mm CsI detector, read out by a photodiode allowing us to measure protons up to 70 MeV. In this first experiment only 4 telescopes were available. The telescopes were placed at 20 cm from the target and covered laboratory angles from 54° to 82° . This setup yielded a recoil angle measurement with an accuracy of 0.3° . Low energy particles which stopped in the strip detector were identified by an energy and a time of flight measurement and higher energy particles by the ΔE -E method. The time resolution of the strip detector was better than 1 ns.

Two low pressure multi-wire proportional chambers [5] were used for beam tracking and one of them furnished the start signal for the time of flight measurement. The scattered projectiles were detected in the SPEG spectrometer in coincidence with recoiling light particles.

Fig.1 displays elastic angular distributions measured for ^{18}O and ^{20}O . The solid lines correspond to coupled channel predictions using the ECIS code [6]. The optical potential was obtained from the Becchetti-Greenlees parameterization [7] developed for proton scattering on medium heavy nuclei. A remarkably good agreement is observed between the calculation and the data for both nuclei. It is noted that no arbitrary normalization is involved here.

CONCLUSIONS

The use of Silicon-strip arrays is a powerful method to obtain high resolution light particle scattering data for unstable nuclei. Proton scattering on ^{20}O and ^{18}O was recently studied at GANIL by using the MUST array. Preliminary results show that elastic scattering angular distributions are in good agreement with coupled channels

calculations using macroscopic optical potentials. A microscopic analysis, which will be undertaken in the near future, should give information on the differences of the density profiles between ^{20}O and ^{18}O . Moreover, the inelastic scattering data will yield transition strengths for the first 2^+ and 3^- states and comparison of these values with microscopic calculations should give information on the structure of the ^{20}O nucleus.

Apart from the $^{20}\text{O}(p,p')$ experiment described above, measurements of proton scattering on ^6He , ^{30}S and ^{34}Ar have recently been performed at GANIL. The versatility of the MUST array will allow studies of transfer reactions and 2-proton decay when the SPIRAL facility comes on-line in the near future.

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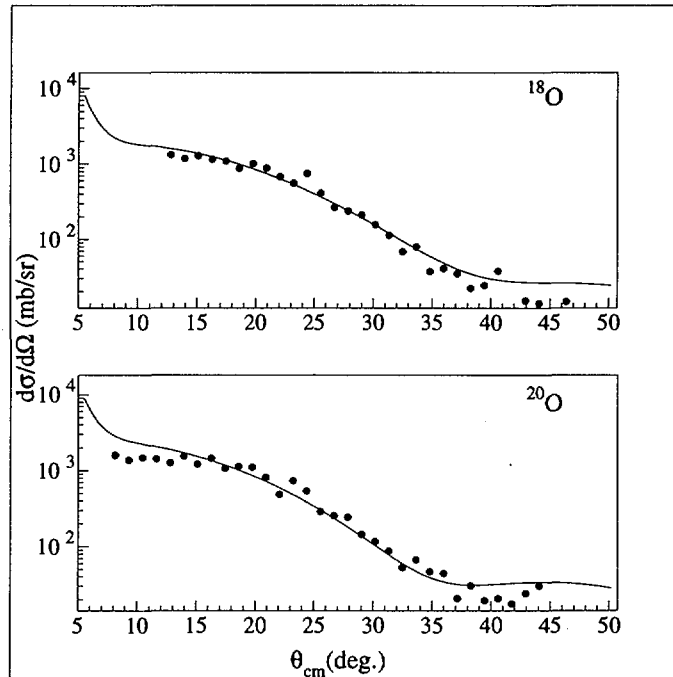


FIGURE 1. Angular distributions for the $^{18}\text{O}(p,p)$ and ^{20}O reactions at 43 MeV/nucleon. Solid lines correspond to calculated angular distributions using the ECIS code.

Anomalous E1 and E2 Strengths in ^{40}Ca and ^{48}Ca at low excitation energy : A Comparative Study

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Can the addition of neutrons modify the structure of nuclear isotopes to the point of affecting their Giant Resonances ? This is a particularly important question in light of the current general interest generated by neutron halo nuclei in which low energy resonances are expected. We present here the results of an experimental comparative study of the $^{40,48}\text{Ca}$ resonance spectra between 6 and 12 MeV. The power of the heavy ion reaction $^{40,48}\text{Ca}(^{86}\text{Kr}, ^{86}\text{Kr}')^{40,48}\text{Ca}^*$ at 60 MeV per nucleon was exploited to enhance greatly the low energy part of inclusive spectra in order to look for the possible presence of a low energy dipole mode in ^{48}Ca due to a neutron skin. We did not observe any difference in the $l = 1$ channel and therefore found no evidence of this mode. In the $l = 2$ channel, an important excess of strength was observed in ^{40}Ca compared to ^{48}Ca . These results challenge traditional RPA descriptions of dipole and quadrupole resonances and suggest that a refinement of our theoretical understanding of giant resonances is necessary to explain the data.

To what extent does the addition of eight neutrons modify the structure of ^{48}Ca compared to the doubly magic ^{40}Ca ? Are these modifications, if any, likely to affect also the collective observables like giant resonances ? These are important questions in nuclear structure especially in light of the current interest generated by neutron halo low energy vibration modes expected to occur in unstable neutron-rich nuclei. In ^{48}Ca , the precursor of such phenomena could be seen as an out-of-phase oscillation of the $f_{7/2}$ neutrons against the $N=Z=20$ core. This would manifest itself as a decoupling of the E1 strength from the GDR and appear as a small low energy $l = 1$ resonance. Several years ago, Harvey and Khanna studied the occurrence of enhanced low energy resonances in ^{208}Pb and showed that their strength and position would be sensitive markers of the parameters of the nuclear force [1]. More recently, Chambers et al. [2] used the RPA in the density functional method to predict the occurrence in neutron rich calcium isotopes of a "soft" E1 resonance. The calculated transition density shows the onset of such a "soft" E1 mode whose strength would increase linearly with neutron number, its largest signal standing at around 8 MeV in ^{48}Ca and exhausting about 5% of the E1 EWSR. Since all RPA calculations predicted the onset of the GDR to be seen well above 15 MeV in both isotopes, the position and strength of the weaker E1 resonance in ^{48}Ca should be visible in a comparison of $l = 1$ spectra of ^{40}Ca and ^{48}Ca since it should not appear in the ^{40}Ca spectrum.

A similar comparison in the $l = 2$ channel is also very interesting. Indeed, experimental results for ^{40}Ca are scattered : measured strengths of the GQR mainly stand around 50% of the EWSR but can vary up to 80% ([3-7]). This is anyway low compared to conventional RPA calculations which predict that this resonance exhausts almost 100% of the EWSR, with the same structure in both ^{40}Ca and ^{48}Ca with a centroid at $E=16$ MeV and half-width of about 5 MeV (there is thus no theoretical basis to expect the occurrence of such a large spreading width in calcium). Recently, Kamerdzhiev et al. [8] have suggested that effects beyond RPA, like ground state correlations induced by particle-hole -phonon coupling would redistribute some of the E2 strength to lower energy and produce a splitting of the familiar GQR. In ^{48}Ca one would expect ground state correlations to be of a different nature than in ^{40}Ca , leading there to a different distribution of quadrupole strength.

Thus, in both $l = 1$ and $l = 2$ channels, a comparative study of the ^{40}Ca - ^{48}Ca spectra is likely to yield interesting insight in the structure of giant resonances and their low energy manifestations. It is the purpose of this Letter to present results of such an investigation.

Heavy ion inelastic scattering is a very efficient tool to investigate low excitation energy states. Indeed, the strong Coulomb excitation provided by a high energy and high Z projectile *results in an enhancement of the very low energy part of the excitation cross section* [9,10]. For instance, for E1 transitions the differential cross section can be written as :

$$\frac{d^2\sigma}{d\Omega dE} = \left(\frac{d^2\sigma}{d\Omega dB(E1)} \right)_E b_{E1}(E) \uparrow$$

where $(d^2\sigma/d\Omega dB(E1))_E$ is the DWBA cross section evaluated at excitation energy E for unit excitation strength,

$B(E1) \uparrow = 1e^2 fm^2$. This cross section represents the pure Coulomb excitation generated by the colliding nuclei for uniform transition strength. The nuclear response to this solicitation is introduced via $b_{E1}(E) \uparrow = dB(E1) \uparrow / dE$, the distribution of E1 reduced matrix element per unit energy, which can be related to the photonuclear cross section $\sigma_\gamma(E)$ by :

$$b_{E1}(E) \uparrow = \frac{9\hbar c}{16\pi^3} \frac{\sigma_\gamma(E)}{E}$$

The Coulomb excitation probability is a decreasing exponential function of excitation energy. As an example, the effect of the combination of the photoabsorption spectrum and the Coulomb excitation probability is shown in figure 1 in the case of $^{84}\text{Kr} + ^{48}\text{Ca}$ inelastic scattering. The left part shows the results of Chambers et al. [2] for the photonuclear cross section in ^{48}Ca . The broad resonance around 8 MeV is the "soft" E1 resonance mentioned above, exhausting about 5% of the EWSR. The right part is a calculation using these results combined with the formalism described above, for the $^{84}\text{Kr}(^{48}\text{Ca}, ^{48}\text{Ca}^*)^{84}\text{Kr}$ reaction at 60 MeV/nucleon at an angle of 2.2 degrees in the center of mass frame. The results are striking in that one observes that the photoabsorption spectrum is greatly distorted by the diffusion with krypton, the low energy part of the spectrum being "amplified" with respect to the high energy side. The cross section of the "soft" resonance becomes even more important than the usual GDR's one, centered around 19 MeV. This demonstrates the power of the inelastic scattering of heavy ions for the study of low excitation energy transitions, such as the soft E1 resonance.

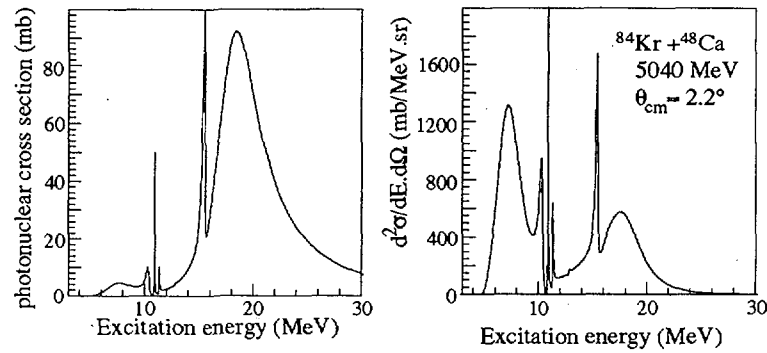


FIG. 1. Comparison between a photoabsorption spectrum calculated by Chambers et al. [2] (left side) and a calculation using these results combined with the Coulomb excitation for the reaction $^{84}\text{Kr}(^{48}\text{Ca}, ^{48}\text{Ca}^*)^{84}\text{Kr}$ at 60 MeV per nucleon (right side) at an angle of 2.2 degrees in the center of mass frame.

Therefore, we have performed an experiment at GANIL, with a ^{86}Kr beam at 60 MeV/nucleon impinging on two thin (about 0.5 mg/cm^2) targets of ^{40}Ca and ^{48}Ca . The targets were fabricated, transported and installed in the scattering chamber under vacuum, to avoid any oxydization. There was no detectable impurity. The scattered ^{86}Kr , in the charge state 35^+ , were detected and identified in the high resolution spectrometer SPEG, in which their scattering angle and energy were measured with an accuracy of 0.2 degree and 1.4 MeV ($\Delta E/E = 2.7 \cdot 10^{-4}$) respectively. The spectrometer was centered at 2.2 degrees in the laboratory frame, covering an angular range from 0.3 to 4.2 degrees. The elastic and low energy inelastic scattering were partly suppressed by insertion of movable absorbers before the focal plane. The excitation energy was measured from about 5 MeV as can be seen on figure 2, and up to several hundreds of MeV. Due to the energy resolution, the low excitation energy transitions are superimposed on a strong tail of the elastic scattering which is highly probable. The spectra shown here are not normalized since the targets' thicknesses were not known precisely and the charge state distribution of the outgoing ^{86}Kr was not measured. Therefore, the absolute normalization of the data was obtained using GDR and GQR results of ref. [5] for the excitation energy between 13 and 25 MeV. We have subtracted a constant background (following the results obtained in [7]) whose angular distribution was assumed to be similar to the angular distribution of the energy region located immediately above the giant resonances region. The consistency of this normalization method was verified with elastic scattering for the ^{40}Ca target, indicating that the strengths measured in [5] are correct within experimental errors. The uncertainty on the absolute normalization is more important for ^{48}Ca , for which data in ref. [5] are less precise ($89 \pm 27\%$ for ^{48}Ca compared to $86 \pm 11\%$ for ^{40}Ca for the giant quadrupole resonance).

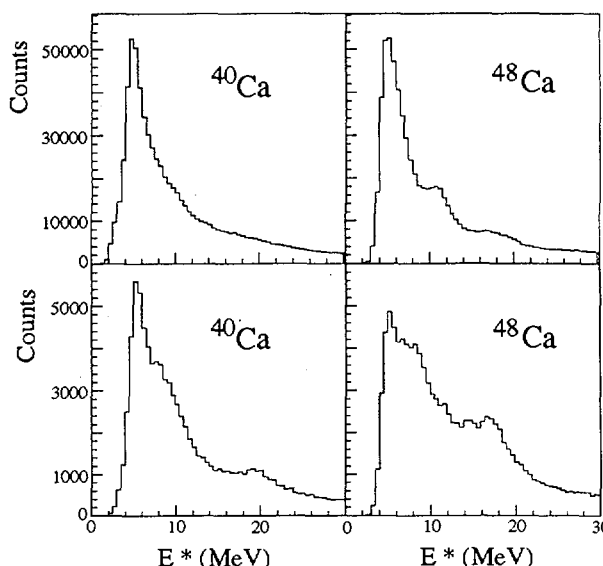


FIG. 2. Excitation energy spectra obtained with ^{40}Ca (left side) and ^{48}Ca (right side) targets, for $0.85 \text{ deg} < \theta_{cm} \leq 1.15 \text{ deg}$ (upper part) and $2.05 \text{ deg} < \theta_{cm} \leq 2.35 \text{ deg}$ (lower part) where dipole transitions dominate. The spectra binning is 500 keV.

Using these data, we have extracted the E1 and E2 transition strengths for both targets and for different bins in excitation energy. Since we cannot distinguish between target and projectile excitations, the strengths determined here concern the whole system. But ^{86}Kr excitations show up in the same way with both targets, allowing us to make a comparative study of the calcium isotopes. A typical example is shown in figures 3 and 4. The cross section is plotted as a function of scattering angle in the center of mass system for an excitation energy between 6 and 8 MeV for both targets. Since we consider all kind of transitions, collective and single particle ones, and we make a comparative study of both targets, no background was subtracted. The grey area around the data corresponds to the uncertainty on the absolute global normalization factor applied to each point of the angular distribution. The data are fitted with calculations performed with ECIS, in the framework of coupled channels equations [11], using E1 and higher multipolarity electric transitions. These higher multipolarity transitions nevertheless should be dominated by $l=2$ ones and therefore we performed the calculations with quadrupolar transition strength only. It should be noted that any small contribution of higher multipolarity would strongly decrease the strength attributed here to quadrupolar transitions. One can see that the behaviors of the two contributions with scattering angle are very different, allowing to determine the only combination of $l=1$ and $l=2$ cross sections reproducing the data. The relative contribution of each kind of transitions is therefore well determined. The uncertainty on the normalization factor, by far dominating other sources of error (particularly the multipolarity decomposition error), defines the precision on the absolute strength extracted for $l=1$ and $l=2$.

The calculations are indeed very close to the experimental values for angles larger than 2.2 degrees. The discrepancy at lower angles comes from the elastic and inelastic to low lying states scattering tail which are not taken into account in the calculations. The contribution of these processes is very difficult to evaluate on account of the many low energy excited states of both targets and projectile. From 2.2 degrees, the contribution of elastic scattering is not dominating anymore, as can be seen on figure 2.

The E1 and E2 strengths extracted are summarized in table I. Note that calculations have been done assuming $l=1$ and $l=2$ excitations of the calcium targets only. For ^{40}Ca target and for $8 \text{ MeV} < E^* < 10 \text{ MeV}$ and $10 \text{ MeV} < E^* < 12 \text{ MeV}$, we have introduced 5% of EWSR for monopole transitions, following the results of [6]. For ^{48}Ca , according to Kameardzhiev [12], the monopolar strength in this excitation energy region can be neglected and this difference between the two isotopes is caused by the difference in shell structure of the two nuclei. Above 10 MeV, the strength cannot be attributed to krypton excitations due to neutron emission.

The analysis of our $l=2$ data indicates that there is a significant difference between the two targets for E2 strength below 12 MeV, with about 15% more E2 strength detected in the scattering on the lighter isotope. As mentioned earlier, this departure from RPA predictions can be explained by invoking the presence in that nucleus of strong ground state correlation effects [8]. There is no indication however why these mechanisms should be so much weaker in ^{48}Ca as to reduce their contribution by the factor observed here.

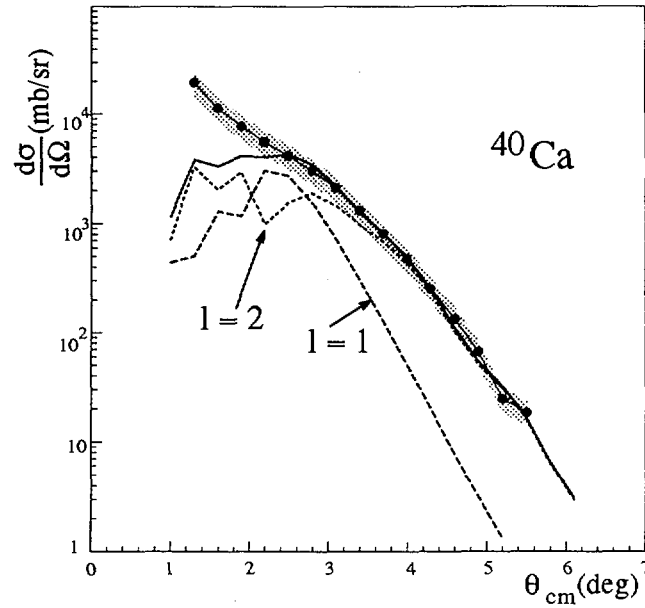


FIG. 3. Angular distribution obtained with the ^{40}Ca target, for $6\text{MeV} < E^* < 8\text{MeV}$. The grey area represents the uncertainty on absolute normalization. The fit obtained with a coupled channel calculation is indicated by the solid line. The dashed lines respectively represent E1 and E2 transitions only.

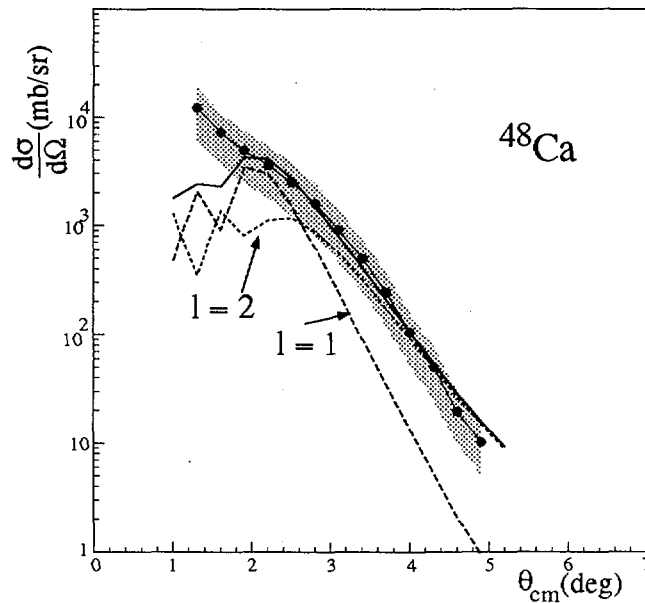


FIG. 4. Angular distribution obtained with the ^{48}Ca target, for $6\text{MeV} < E^* < 8\text{MeV}$. The grey area represents the uncertainty on absolute normalization. The fit obtained with a coupled channel calculation is indicated by the solid line. The dashed lines respectively represent E1 and E2 transitions only.

In the $l = 1$ case, two general observations come to mind :

- 1) One observes non negligible E1 strength with both targets in the low excitation energy region studied here. There is no theoretical basis for such a strength, since all RPA calculations (*with or without* ground state correlations) predict no E1 strength below 14 MeV in either isotope except in [2] for ^{48}Ca .
- 2) We do not observe any E1 strength difference between ^{48}Ca and ^{40}Ca . Therefore, there is no evidence of the excitation of a soft dipole mode in ^{48}Ca . Nevertheless, the E1 strength observed between 8 and 10 MeV is indeed consistent with the predictions of Chambers et al. [2]. A better study of the low excitation energy spectrum of $^{40}, ^{48}\text{Ca}$ could be achieved in the forthcoming years with the improved energy resolution of the new focal plane detection of

SPEG. The expected energy resolution of 150 keV would allow to study whether the strength observed in ^{48}Ca possesses the collective features i. e. resonance shape and transition density, expected for the soft E1 mode [2].

In conclusion, the results of our experiment using a particularly powerful and efficient probe for detecting low-lying excitations suggest that, in the E1 and E2 cases, our theoretical understanding of collective excitations should be critically reassessed. This is becoming especially important as higher resolution facilities are coming on line which will further test our understanding of the microscopic structure of collective excitations, as well as their coupling to more complex degrees of freedom.

E(MeV)	^{40}Ca		^{48}Ca		Difference	
	$l=1$	$l=2$	$l=1$	$l=2$	$l=1$	$l=2$
[6,8]	2.6 ± 0.6	8.3 ± 2.0	3.1 ± 1.5	4.2 ± 2.1	-0.5	+4.1
[8,10]	4.9 ± 1.2	15.6 ± 3.9	3.6 ± 1.8	8.8 ± 4.4	+1.3	+6.8
[10,12]	6.6 ± 1.6	15.8 ± 3.9	7.0 ± 3.5	10.0 ± 5.0	-0.4	+5.7

TABLE I. Percentage of the EWSR extracted from the data for $l=1$ and $l=2$ transitions for three energy regions. The errors are determined by the uncertainty on absolute normalization. The error due to multipolarity decomposition is negligible compared to this error. The percentage difference between ^{40}Ca and ^{48}Ca is given in the last column. The total strength between 6-12 MeV cannot be read as the cumulative sum because of the common boundaries. For ^{40}Ca target and for $8\text{MeV} \leq E^* \leq 10\text{MeV}$ and $10\text{MeV} \leq E^* \leq 12\text{MeV}$, we have introduced 5% of EWSR for monopole transitions, following the results of [6].

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SPECTROSCOPY OF THE UNBOUND ^{11}N NUCLEUS BY THE $^{12}\text{C}(^{14}\text{N}, ^{15}\text{C})^{11}\text{N}$ TRANSFER REACTION

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Many interesting phenomena occur in the isobaric chain of nuclei with mass 11. The two-neutron halo of the ^{11}Li , the $s_{1/2}$ intruder halo ground state of the Be^{11} are some examples. The stability island is crossed from one shore to other with the five $A=11$ nuclei. The unbound ^{11}N is the mirror nucleus of ^{11}Be at the other end of the $T=3/2$ isospin quartet. It has been the object of many recent studies, mainly to establish if the spin inversion persists and the ground state is the continuum equivalent of a proton halo. However the observation of an unbound $s_{1/2}$ resonance is a difficult task due to the lack of centrifugal barrier, which makes the width of the resonance fairly large. Previous experiments [1,2] claim the observation of the s-wave ground state resonance.

The spectroscopic study of the ^{11}N was performed by using the $^{12}\text{C}(^{14}\text{N}, ^{15}\text{C})^{11}\text{N}$ transfer reaction [3]. The experience was realized at GANIL with a ^{14}N beam of 30 A MeV incident energy using the SPEG spectrometer for the ejectil analysis. The selectivity, momentum calibration and resolution are also well demonstrated for other product nuclei as ^{12}N and ^{13}N .

The quality of the spectrum of the $^{12}\text{C}(^{14}\text{N}, ^{15}\text{C})^{11}\text{N}$ reaction seems to be better than of previous measurements [1,2,4]. It presents several well defined resonances in the ^{11}N with the ^{15}C ejectile in its $5/2^+$ excited state. The $1/2^+$ ground state of the ^{15}C is much less favoured in this transfer reaction. The ^{11}N resonances observed in the spectrum have the decay energies (with respect to the $^{10}\text{C}+p$ threshold) of $E_{\text{decay}}=2.18(5)$, $3.63(5)$, $4.39(5)$, $5.12(8)$ and $5.87(15)$ MeV. The first two resonances correspond respectively to the fairly pure single-particle $p_{1/2}$ and $d_{5/2}$ levels, previously observed. For the higher resonances the spin-parity assignments are difficult, their structure can involve also core excitations and the estimated values of $3/2^-$, $5/2^-$ and $7/2^-$ are only preliminary. Our observed widths are lower than those previously observed, possibly due to our energy resolution.

There is no clear evidence of the population of the $s_{1/2}$ ground state of ^{11}N in this experiment; however, our spectra of ^{12}N and ^{13}N , which have much better statistics, clearly corroborate the strong hindrance of any $2s_{1/2}$ resonance. This does not exclude the existence of the $s_{1/2}$ resonance in ^{11}N , but reopens the debate about the missing s state.

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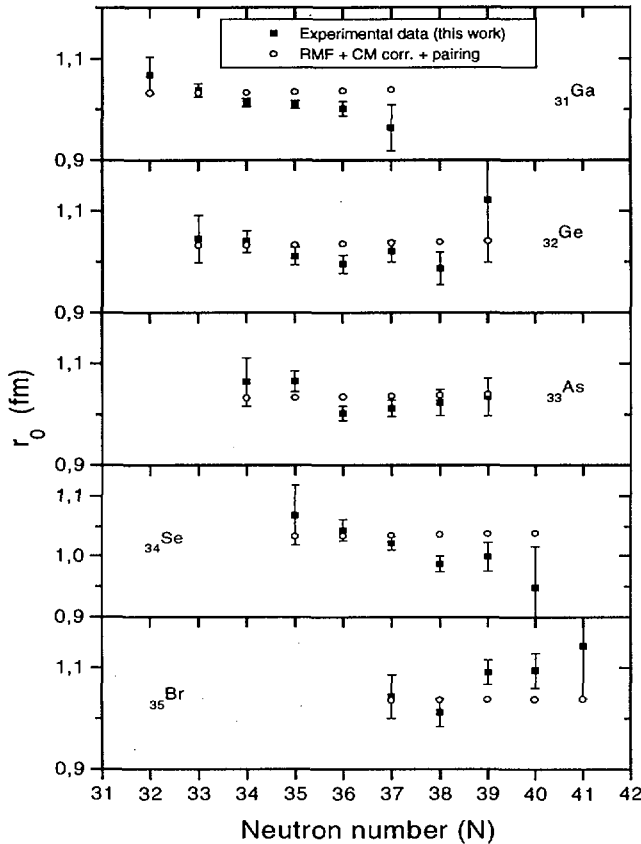
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NUCLEAR RADII OF PROTON-RICH RADIOACTIVE NUCLEI AT A=60-80

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The region of neutron-deficient nuclei with $A \sim 60-80$ near the $N=Z$ line presents interesting properties as shape-coexistence and reinforcing or switching of shell-gaps [1]. Very near to the spherical magic



number 40 strong ground-state deformations ($\beta_2 \sim 0.44$) were found in the ^{76}Sr ($Z=N=38$) and $^{74,76}\text{Kr}$ ($Z=36, N=38,40$) nuclei, while neighbouring nuclides with lower Z values, as $^{70,72}\text{Ge}$ ($Z=32, N=38,40$) and $^{72,74}\text{Se}$ ($Z=34, N=38,40$) present spherical behaviour around $N=38$ [1]. One first simple information concerning the deformations of nuclei in this region can be obtained from their radii, which can be deduced from the experimental data of reaction cross sections. Therefore we measured at GANIL (Grand Accélérateur National d'Ions Lourds), Caen, France the radii of proton-rich radioactive nuclei with masses between $A=60-80$ near the $N=Z$ line. They were produced via the fragmentation of a 73 MeV/nucleon ^{78}Kr primary beam on a ^{nat}Ni target. The secondary beams were analysed in the high precision magnetic spectrometer SPEG with complete identification of mass and atomic number of the incident particles. The nuclear reaction cross section of secondary nuclei on Silicon were measured using the Direct Method [2], where the detector plays also the role of the target. The reduced nuclear radii r_0 , defined by Kox [3] from a large systematics using stable nuclear radii, can be obtained from the direct reaction cross-section [4]. The results of r_0 for $^{63,64,65,66,67}\text{Ga}$, $^{65,66,67,68,69,70,71}\text{Ge}$, $^{67,68,69,70,71,72}\text{As}$, $^{69,70,71,72,73,74}\text{Se}$ and $^{72,73,74,75,76}\text{Br}$ are presented in the figure, compared with theoretical predictions. The nuclear densities were obtained in a spherical relativistic mean field (RMF) with center of mass correction including pairing correlation [5]. Finally Glauber calculations were performed to obtain the reaction cross sections and the values of the reduced radius r_0 . The experimental radii are not constant as a function of N , presenting a minimum around $N=36-38$, possibly corresponding to the spherical configuration. For lower, as well as for higher N values the r_0 values increase. The spherical RMF calculation gives a reasonable agreement, without reproducing the systematic trend of a minimum around $N=38$.

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Study of subshell closure at $N=40$ by Coulomb excitation

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Coulomb excitation experiment has been achieved in order to study the subshell closure at $N = 40$ for neutron-rich nuclei. This subshell effect is thought to be enhanced when large N/Z ratios are encountered. Therefore, the $Z = 28$ ^{68}Ni is of particular interest in order to test this behaviour. In addition this nucleus would be a good starting point for describing other nickel isotopes up to the doubly magic ^{78}Ni . Some experimental informations are already known for ^{68}Ni at low excitation energy : a 0_2^+ isomer at 1.770MeV ¹⁾, a 2^+ state at 2.033MeV ²⁾ and a long-lived 5^- state at 2.847MeV ²⁾. The high energy of the 2^+ state suggests the shell closure though its reduced transition probability $B(E2)$ has never been measured.

The experiment, performed at GANIL with the LISE3 spectrometer, has been investigated by the method of Coulomb excitation of secondary beams into a thick target placed in the center of a large gamma-array detector. The nuclei were produced at an energy of about 50 A.MeV by the fragmentation of a ^{86}Kr beam at 65 A.MeV on a Ni target.

Secondary beams were identified event-by-event by two large-area (25 cm^2) silicon detectors mounted at a distance of 50 cm from the secondary lead target (220 mg/cm^2). Two clover Ge-detectors were placed around the implantation detector in order to determine photons originating from the decay of isomers transmitted by the spectrometer. Deflection angle of the fragments (up to an angle of 3° in the laboratory frame) can be determined by position sensitive gas detectors located before and after lead target. At these small deflection angles, Coulomb inelastic contribution dominates the total cross-section. The lead target was surrounded by the 70 BaF_2 detectors of "Château de Cristal" mounted at a distance of 35

cm, in the 4π geometry of the first generation TAPS-detector. The production rate of fragments was about 100 particles/second for ^{76}Ge and ^{72}Zn , and about 20 particles/second for ^{68}Ni and ^{70}Zn . γ -rays originating from Coulomb excitation are emitted in flight with a velocity of $v/c=0.3$.

Time-resolution between an incoming projectile and γ -ray in the total array is better than 3 ns. Achieved energy spectra are shown on Fig. 1.

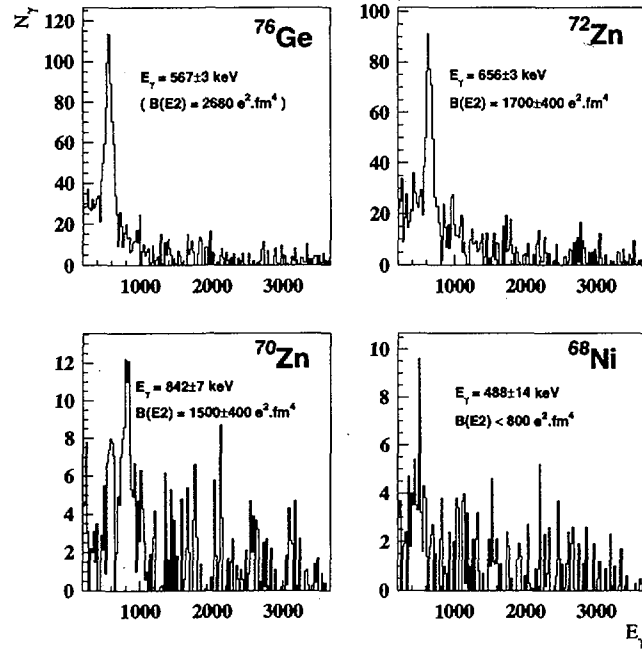


Figure 1: Doppler corrected energy-spectra and excitation probability obtained from Coulomb excitation of ^{76}Ge , ^{72}Zn , ^{70}Zn and ^{68}Ni . The x-axis is in keV.

^{76}Ge is a well-known case of deformed nucleus with a low 2^+ state (562.9 keV) and a strong excitation probability ($B(E2)^\uparrow = 2680 \text{ e}^2 \cdot \text{fm}^4$). It has been used as a reference in order to determine $B(E2)$ for other nuclei (^{72}Zn , ^{70}Zn and ^{68}Ni). Even if the spectrometer wasn't optimized for ^{70}Zn , an excitation probability value has been determined for the 2^+ state at $830 \pm 75 \text{ MeV}$: $B(E2) = 1500 \pm 400 \text{ e}^2 \cdot \text{fm}^4$. With regard to ^{68}Ni , very few counts are found around the expected energy (2.03 MeV). Hence only an upper limit has been derived: $B(E2) \leq 800 \text{ e}^2 \cdot \text{fm}^4$. This limit doesn't establish sphericity of this nucleus. Nevertheless a structure is yet visible around 490 keV, whose structure isn't still clear. Two assumptions can be made: on one hand, it could be a signature of the decay in flight of the 0_2^+ isomer, on the other hand, it could be due to the Coulomb excitation of one of the both isomers, present in the ^{68}Ni beam as a contaminant.

Future investigations with majors improvements at GANIL are planned. First the use of a neutron-rich primary beam ^{70}Zn , closer to ^{68}Ni will enhance the production rate with a factor of at least 100, and secondly a higher resolution γ -array composed with segmented clover Ge detectors will increase the sensitivity of the set-up.

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Interplay between the neutron halo structure and reaction mechanisms in collisions of 35 MeV/nucleon ${}^6\text{He}$ with Au.

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The halo structure of some nuclei has been mainly probed so far by considering the linear momentum distributions of either the core or the neutrons or both, emerging from breakup reactions. However, in most experiments, rather little attention has been paid to the influence of the reaction mechanism or to the considered reaction channels on these observables. At best, the choice of the target nucleus, either very heavy or very light, was made with the aim of either enhancing or inhibiting Coulomb breakup. Moreover, in many cases a rather simple experimental device was used not permitting both an energy and angular exploration of the detected cores, making most of these first generation experiments integral experiments. Furthermore, no attempt has so far been made to experimentally quantify the excitation energy deposited into the target-nucleus, which appears to be as an extremely valuable piece of information for characterizing the reaction channels.

Utilizing the experimental device sketched in Fig.1, the following reaction products were measured eventwise:

- the ${}^4\text{He}$ projectile core (or its component(s) when breaking up) through its parallel and transverse linear momenta.
- the halo neutron(s) via its (their) momentum modulus.
- the target excitation energy through the multiplicity of evaporated neutrons.

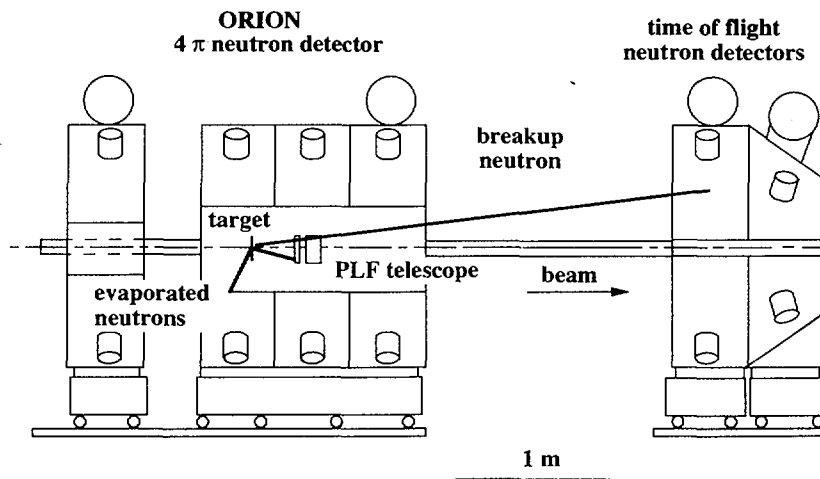


Fig.1: Schematic view of the experimental setup.

For the first time, when using all these measured parameters it was possible to follow the linear momentum distribution widths, for both the core and the halo neutrons, over a very broad domain of impact parameters and distinct reaction channels. The general trend observed in Fig.2 is an increase of the momentum widths for reactions presumably associated with smaller impact parameters. The probing of different parts of the wavefunction for different impact parameters on one hand and different final-state interactions, both in nature and magnitude, on the other hand are likely to be responsible for this behavior¹⁾. Most of the published data so far were obtained in rather inclusive experiments and may thus depend considerably on the experimental conditions (position and opening angle of the detectors). This stresses the need of exclusive data for other halo nuclei might they be single- or double-neutron halos.

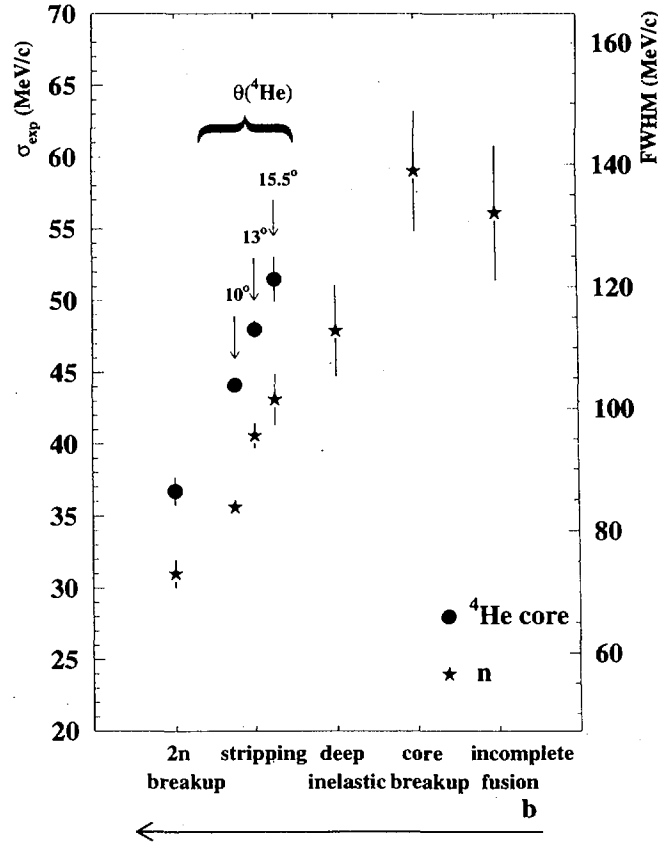


Fig.2: Comparison between the widths of the parallel momentum distributions of the core nucleus (dots) and the halo neutrons (stars) for the different reaction channels isolated in the experiment.

The present experiment has also shed new light on the nuclear structure of the ${}^6\text{He}$ nucleus. According to theoretical predictions the ground state should appear with two configurations equally probable: one with the two neutrons as a di-neutron, the other with the two neutrons opposite with respect to the core, thus giving the nucleus a cigar-like shape. This could be checked experimentally, based on the following arguments. In stripping reactions there is a large probability to remove the two neutrons in the first configuration whereas this probability should be low in the second configuration. By measuring the probability for the one-neutron stripping and the two-neutron stripping one tends to confirm the predicted structure. However more data are needed as a function of impact parameters in order to be more quantitative.

In summary, a new approach has been followed in the investigation of neutron halo nuclei. Very exclusive data have shown the importance of reaction mechanisms in connection with the nuclear structure. A good understanding of the reaction mechanism appears to be a prerequisite to the investigation of the nuclear structure.

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Exotic Molecular and Halo States in $^{12,14}\text{Be}$

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Abstract. The two nuclei ^{12}Be and ^{14}Be have been studied using breakup reactions on p, ^{12}C and ^{208}Pb targets. The decay of ^{12}Be into two helium clusters ($^6\text{He}+^6\text{He}$ and $^4\text{He}+^8\text{He}$) was observed from a series of excited states between 10 and 25 MeV, with spins in the range 4^+ to 8^+ . The single neutron angular distributions for ^{14}Be exhibit the narrow forward peak characteristic of a halo. The widths of these distributions in coincidence with ^{12}Be fragments are $\Gamma_L=78\pm6$ and 80 ± 1 MeV/c for breakup on carbon and lead.

I INTRODUCTION

The stability of the α -cluster has a strong influence on the structure of light nuclei and has spawned an industry devoted to the understanding of the role of clustering in s-d shell nuclei dating from the early 1960's when heavy-ion beams were first exploited. The advent of radioactive beams has also revealed clustering in light, neutron-rich nuclei, in the guise of the halo, where the nucleus is composed of a core and valence halo neutrons, and the molecular type cluster states composed of α -particles bound by the valence neutrons.

In the 1960's, Ikeda [1] developed a classification of clustering in light $A=4n$, α -conjugate nuclei, in which cluster structures appeared at, or close to, the decay threshold for the particular cluster partition. This scheme, which is on the whole verified by experimental observations, is based on the premise that to create the internal cluster structures an energy equivalent to the binding energy of the constituents is required. Thus systems that include weakly bound neutrons, e.g. ^{11}Be ($S_n=0.5$ MeV) and ^{11}Li ($S_{2n}\simeq 0.3$ MeV), should show strong clustering characteristics. Clustering is amplified in these systems by reduced centrifugal barriers for the weakly bound valence neutrons allowing a greater decoupling of the core and halo neutrons. The heaviest particle stable Be isotope, ^{14}Be ($S_{2n} = 1.34 \pm 0.11$ MeV), is Borromean and is known to exhibit a two-neutron halo. In contrast to other halo systems, the configuration of the valence neutrons is expected to contain a significant d-wave admixture. Additionally, ^{14}Be is the heaviest two-neutron halo nucleus currently known. The investigation of ^{14}Be , presented here, thus provides an opportunity to study the evolution of halo systems with binding energy, angular momentum and mass.

Another extreme manifestation of clustering is the formation of chain and ring structures composed of individual cluster units, such as α -particles. Indeed there is some evidence for such structures in light nuclei. Similar arrangements have also been observed in atomic systems, for example carbon clusters [2] which are believed to be related to particular spectral lines in astronomical observations of stellar dust clouds. Another nuclear analogue of such phenomena are α -ring and chain structures covalently bonded by valence neutrons, predicted by Wilkinson [3], much as the binding of atomic molecules through the exchange of electrons. Von Oertzen [4] has characterized the structure of the sequence of Be isotopes ^9Be to ^{11}Be in terms of dinuclear 2α -Xn structures, and certain carbon isotopes as trinuclear molecules. The present contribution reports a measurement of the 2α -4n cluster system ^{12}Be .

II EXPERIMENTAL MEASUREMENTS

The secondary beams of $^{12,14}\text{Be}$ ($\overline{E}_{^{12}\text{Be}} = 31.5$ MeV/nucleon, $i \approx 2.10^4$ pps, $\overline{E}_{^{14}\text{Be}} = 41.3$ MeV/nucleon, $i \approx 10^2$ pps) were prepared from the fragmentation of an ^{18}O beam (63 MeV/nucleon) on a thick Be target using the LISE3 spectrometer. In

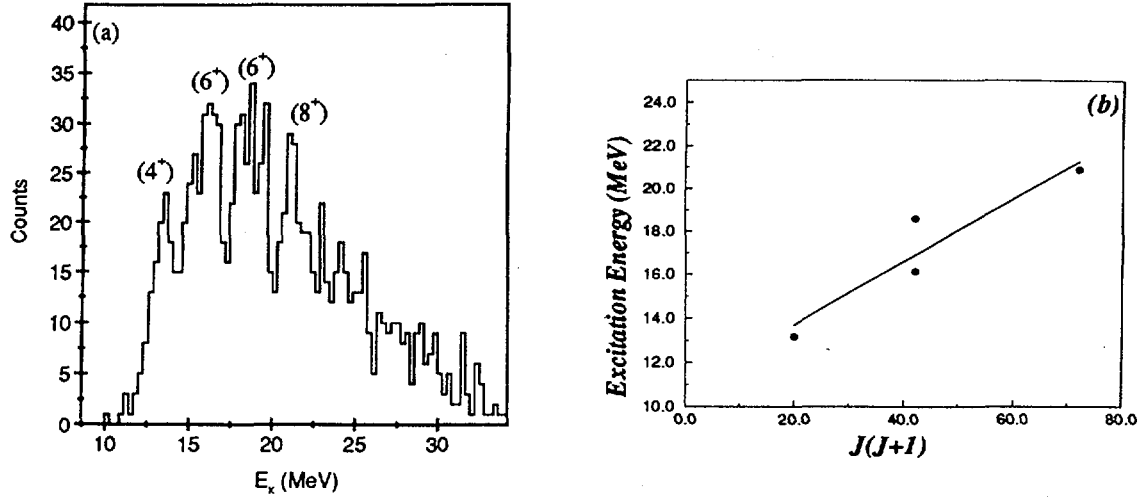


FIGURE 1. (a) ^{12}Be excitation energy spectrum for $^6\text{He}+^6\text{He}$ coincidences, (b) the energy-spin systematics of the breakup states.

the case of the ^{14}Be studies, measurements were carried out on secondary reaction targets of carbon and lead ($\bar{E}_{^{14}\text{Be}} = 35$ MeV/nucleon at target mid-point) in an attempt to disentangle the effects of nuclear and Coulomb induced breakup. For the ^{12}Be measurements, ^{12}C and $(\text{CH}_2)_n$ target foils were used, with beam tracking and time-of-flight measurement provided by two parallel plate avalanche counters. The breakup of the ^{12}Be nucleus into two helium fragments was detected in an array of ten Si-CsI telescopes placed around the beam axis. The silicon elements were two dimensional position sensitive detectors (2DPSDs), proving a measurement of the angle of the incident particles with a resolution of better than 0.5° . The telescopes provided a clean identification of the ^4He , ^6He and ^8He nuclei of interest, and a measurement of the energy with a resolution of 1.5%. For the ^{14}Be experiment the charged reaction products were again detected using the 10 element position sensitive Si-CsI array with one of the elements placed at zero degrees. Neutrons were detected using the 99 modules of the DEMON array. A staggered arrangement

Reaction	Target	σ (mb)
$p(^{12}\text{Be}, ^6\text{He}^6\text{He})p$	$(\text{CH}_2)_n$	0.76 (0.05)
$^{12}\text{C}(^{12}\text{Be}, ^6\text{He}^6\text{He})^{12}\text{C}$	$(\text{CH}_2)_n$	0.26 (0.06)
$^{12}\text{C}(^{12}\text{Be}, ^6\text{He}^6\text{He})^{12}\text{C}$	^{12}C	0.28 (0.04)
$p(^{12}\text{Be}, ^4\text{He}^8\text{He})p$	$(\text{CH}_2)_n$	2.91 (0.06)
$^{12}\text{C}(^{12}\text{Be}, ^4\text{He}^8\text{He})^{12}\text{C}$	$(\text{CH}_2)_n$	1.62 (0.11)
$^{12}\text{C}(^{12}\text{Be}, ^4\text{He}^8\text{He})^{12}\text{C}$	^{12}C	0.79 (0.07)

TABLE 1. ^{12}Be breakup reaction cross sections.

Channel	$\sigma_{\text{telescope}}$ [mb]		Γ_n [MeV/c]	
	C	Pb	C	Pb
^{12}Be	460 ± 40	2300 ± 400	—	—
$^{12}\text{Be} + n$	—	—	78 ± 6	80 ± 1
^{11}Be	85 ± 15	—	—	—
^{10}Be	145 ± 20	—	—	—
$^{10}\text{Be} + n$	—	—	119 ± 44	—

TABLE 2. Preliminary results for the breakup of ^{14}Be on C and Pb targets. The single neutron angular distributions have been characterized in terms of a Lorentzian distribution.

for the neutron detectors was chosen so as to maximize the coverage at forward angles whilst minimizing the effects of cross talk (both geometrically and in the off-line analysis).

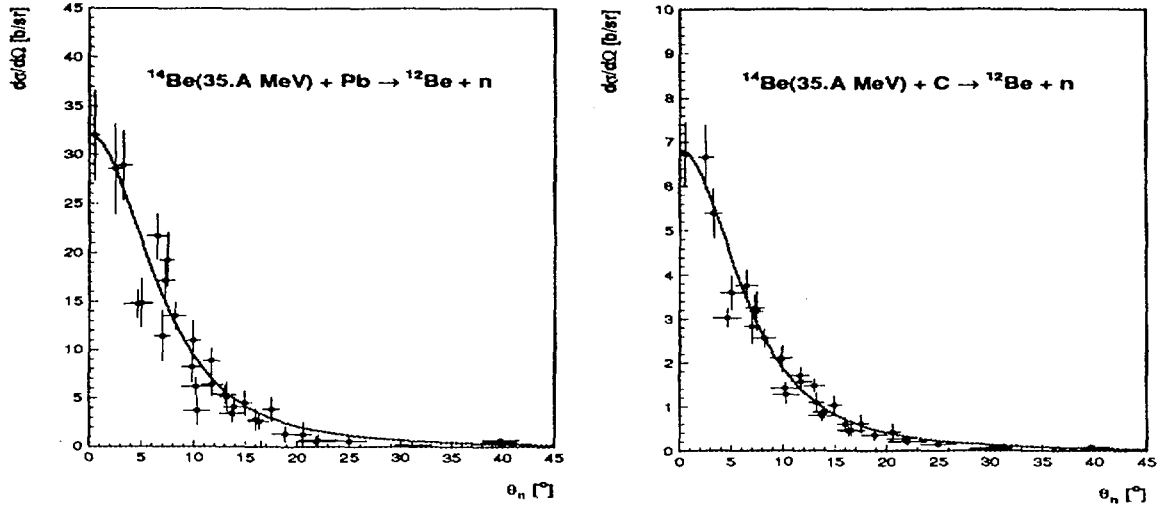


FIGURE 2. Single neutron angular distributions for the breakup of ^{14}Be ($E_n=10$ to 100 MeV).

A ^{12}Be breakup

The Q -values for the reactions $^{12}\text{C}(^{12}\text{Be},^x\text{He}^y\text{He})^{12}\text{C}$ and $p(^{12}\text{Be},^x\text{He}^y\text{He})p$ were calculated from the energies of the two detected helium nuclei and the energy of the undetected recoil-like particle inferred from the measured momenta of the beam and detected reaction products. In the case of the $(\text{CH}_2)_n$ target this technique was able to resolve the reactions taking place on the carbon and hydrogen. The cross

sections for the various reactions are given in Table 1. Selecting events identified with peaks in the Q-value spectra for the above reactions, it is possible to calculate the excitation energy, or invariant mass, of the ^{12}Be nucleus prior to decay using the relationship

$$E_x = \frac{1}{2}\mu v_{rel}^2 + Q_{bu} \quad (1)$$

where v_{rel} is the relative velocity of the two breakup fragments, μ the reduced mass and Q_{bu} the breakup Q-value, which for the $^6\text{He}+^6\text{He}$ and $^8\text{He}+^4\text{He}$ channels is 10.11 and 8.95 MeV respectively. Figure 1a shows the ^{12}Be excitation energy spectrum for decays into two ^6He nuclei. These states, which span the excitation energy region 10 to 25 MeV, are the first definitive evidence for the $2\alpha-4n$, molecular cluster structure in this nucleus [5]. Angular correlation measurements of the breakup products indicate that the states may be associated with spins from 4^+ to 8^+ , and the inferred excitation energy-spin sequence appears to be consistent with a rotational band with a large moment of inertia (Figure 1b).

B ^{14}Be breakup

The ^{14}Be reaction cross sections derived from the telescope data confirm that the two-neutron removal reaction channel is dominant, as seen in an earlier experiment [6]. The single neutron angular distributions (shown in Figure 2) exhibit the narrow, forward peaked form characteristic of a halo. Interestingly the characteristic widths of the distributions for the two targets are very similar and thus may suggest, as in the case of ^{11}Li [7], the existence of a very low lying state in ^{13}Be . The analysis of the $^{12}\text{Be}+n$ invariant mass spectrum, presently underway, should shed further light on this conjecture. The $^{12}\text{Be}+n+n$ invariant mass spectrum is being investigated in parallel with the objective of extracting the low-lying dipole strength function, $dB(E1)/dE_x$. The two-neutron correlations — relative momenta and correlation function, $C(q)$ — are also under analysis, with the present effort concentrating on inclusion of the effects of neutron-neutron final state interactions. The results of these analyses when compared with realistic three-body models are expected to provide important insights into the halo structure of ^{14}Be .

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Quadrupole and magnetic moment of spin-oriented ^{18}N fragments measured with the combined β -LMR-NMR method.

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We have produced spin-oriented projectile fragments by selecting a secondary beam in the forward direction after the reaction of a ^{22}Ne (60.3 MeV/u) beam with a ^{12}C (350 mg/cm²) target. The target was mounted on a rotating target frame in the LISE target chamber. A nearly pure secondary beam of ^{18}N -fragment (5.5 % of ^{20}O contamination) was selected using the LISE spectrometer and the Wien-filter. After reducing the beam energy by Al-degraders, the fragments were stopped in a Mg single crystal, which was mounted on the cold finger of a continuous flow cryostat into a vacuum chamber. The crystal was cooled to 40K, in order to reduce the influence of spin-lattice relaxation on the spin-orientation. A static magnetic field up to 2000 Gauss was induced by two coils mounted around the vacuum chamber. Around the Mg-crystal, a small RF-coil was build to induce a RF-field with constant frequency of 20 kHz. Due to the presence of 3 interactions, a static magnetic dipole interaction ($v_B = g\mu_N B/h$), a static electric quadrupole interaction ($v_Q = eQV_{zz}/h$) and a RF-interaction ($v_{RF} = 20 \pm 3$ kHz), the spin-orientation of the fragment nuclei is modified resonantly at well-defined values for the static magnetic field strength B . The induced spin-polarization is measured by monitoring the β -decay asymmetry as a function of the magnetic field strength. From the position of the resonance fields, we can deduce unambiguously the magnetic moment and the quadrupole moment of the selected projectile fragment [1,2,3]. The measured high-precision LMR is in very good agreement with a first less-precise measurement [3,4,5]. From the NMR-resonances, measured as a function of B (fig. 1), we derive a very small magnetic moment $\mu = 0.157(7)$ n.m.. Using this value together with the ratio μ/Q derived from the LMR-resonance field, we deduce a rather large quadrupole moment $Q = 32(3)$ emb for the ^{18}N , $I^\pi = 1^-$ ground state [6,7]. Comparison to shell model calculations using the USD interaction of Brown and Wildenthal [8] shows that the magnetic moment is smaller than expected. However, modifying slightly the interaction parameters, such that the magnetic moment of the $3/2^+$ first excited state in ^{18}O is reproduced better, gives perfect agreement between experiment and theory [9]. No shell-model calculations for the quadrupole moment have been performed so far. Comparison to mean-field calculations [10], shows an experimental Q -moment which is about 60% larger than the theoretical value for the proton Q -moment, using the rotational model relation with $K=0$ to relate the intrinsic theoretical and measured spectroscopic quadrupole moment ($Q_0 = -(2I+3)/I Q_s$).

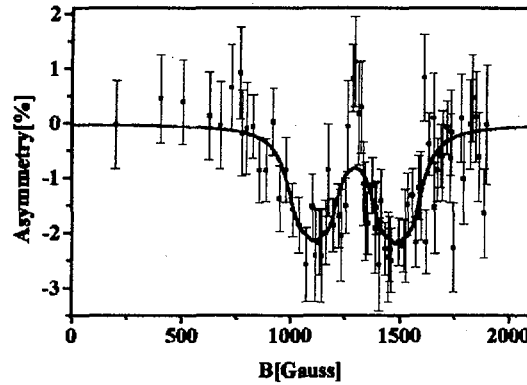


Figure 1 : NMR-resonances : At well-defined magnetic field values, polarization is induced resonantly by applying an RF-field with constant frequency, perpendicular to the static magnetic field. The ^{18}N -fragments are stopped in a Mg single crystal oriented such that it's c-axis nearly coincides ($1^\circ < \beta < 2^\circ$) with B.

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Charge-exchange reaction induced by ${}^6\text{He}$

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Abstract: The charge exchange reaction $p({}^6\text{He}, {}^6\text{Li})$ was studied in reverse kinematics with a secondary ${}^6\text{He}$ beam at 41.6 MeV /nucleon. Angular distributions for the reactions connecting the ground states and the one leading from the ground state of ${}^6\text{He}$ to its isobaric analogue state in ${}^6\text{Li}$ have been obtained between 0° and 20° in the center of mass. The results were analyzed into the context of a microscopic calculation.

Nucleon-nucleus elastic scattering and charge exchange reactions have been widely studied in the past with stable targets and provided valuable information on nuclear properties such as the nucleon-nucleon interaction, energy levels or transition matrix elements [1-2]. It was shown by Lane that the inclusion of the isospin term in the optical potential has the effect of coupling all the channels with the same total isospin [3]. In this way the charge-exchange reaction (p,n) connecting two isobaric analogue states is coupled to the elastic scattering reaction because the structure of the target and the residual nucleus are essentially the same, differing only in the isospin. In this context, a consistent description of the (p,p) and (p,n) angular distributions could provide information on the isoscalar and isovector part of the nucleon-nucleon interaction and could also ideally probe differences between the proton and neutron density distributions [4].

Nowadays, the advent of intense secondary beam facilities allows to extend these studies to unstable nuclei by using secondary radioactive beams and inverse kinematics and test our understanding of the nuclear properties far from the valley of stability.

We have studied the $p({}^6\text{He}, {}^6\text{Li})n$ reaction, which populates two states : the ground state of ${}^6\text{Li}$ via a Gamow-Teller transition (GT) and the 3.56 MeV excited state of the same nucleus, which is the isobaric analogue state (IAS) of the ${}^6\text{He}$ ground state. The 3.56 MeV state of ${}^6\text{Li}$ is predicted theoretically to be a halo state [5]. Therefore this reaction provides the opportunity to

study simultaneously transitions connecting a halo state and either a standard or another halo state.

To analyze the data we have used an optical model potential, obtained by folding the standard JLM interaction [6] for stable nuclei ($\lambda_v=1$, $\lambda_w=0.8$) with neutron and proton densities obtained by Hartree-Fock calculations [7] and assuming that the isoscalar and isovector strengths of the JLM interaction are known from direct reaction studies with stable nuclei. However, these calculations had failed to reproduce the experimental data, Figure 1. In this point, it has to be reminded that a fit to our previous elastic scattering data $p(^6\text{He}, ^6\text{He})p$, had also failed to reproduce the experimental differential cross sections with standard normalization parameters. It was suggested [8] that a good fit could be obtained by adjusting either the real part or the imaginary part of the optical potential. The effect of the normalization of the real and imaginary part of the entrance channel optical potential for the present (p, n) data is shown in Figures 1a and 1b respectively. Fig. 1a shows that it is not possible to reproduce the (p, n) angular distribution by a readjustment of the real potential. However this is possible through the imaginary potential (Fig. 1b). The best fit ($\lambda_v=1$, $\lambda_w=1.8$), which was obtained for the elastic angular distribution, gives also a satisfactory agreement with the charge exchange reaction. This analysis shows that a consistent description of the elastic scattering $p(^6\text{He}, ^6\text{He})p$ and $p(^6\text{He}, ^6\text{Li}_{IAS})n$ charge exchange reaction can be obtained only by assuming a strong renormalization of the imaginary part of the optical potential.

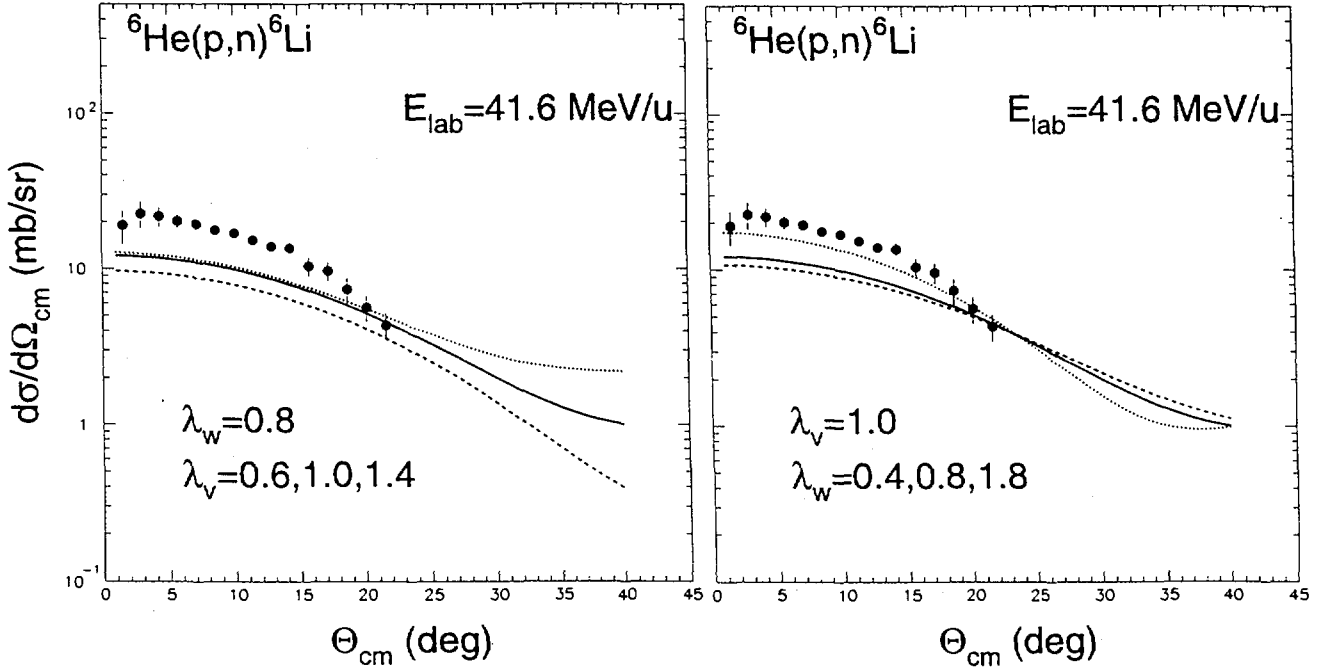


Figure 1: a) Comparison of the present results with JLM calculations adopting different normalization factors for the real part of the potential. b) same for the imaginary part.

Subsequently we have explored the sensitivity of our results against various density distributions. In Fig. 2, the data are compared with JLM predictions obtained with constant real and imaginary normalizing parameters of 1.0 and 1.8 respectively and the following density distributions: a) Hartree-Fock density distributions by Sagawa et al. [7] which give root mean square radii, $R_p=1.90$ fm and $R_n=2.36$ fm for protons and neutrons correspondingly-dashed line b) Similar distributions for both protons and neutron ($\rho_n = (N/Z) \rho_p$) -dot-dashed line (where ρ_p is Sagawa's Hartree-Fock density distribution) c) Distributions calculated, assuming a two Gaussian shape and root mean square radii $R_p=1.88$ and $R_n=2.48$, that is the values obtained from a Glauber analysis of recent $p(^6\text{He}, ^6\text{He})p$ elastic scattering data obtained at high energy ($R_p=1.88\pm0.12$ fm, $R_n=2.48\pm0.11$ [9]) -solid line and d) Distributions calculated assuming a two Gaussian shape and root mean square radii $R_p=1.9$, $R_n=2.36$ that is the Sagawa root mean square radii -dotted line.

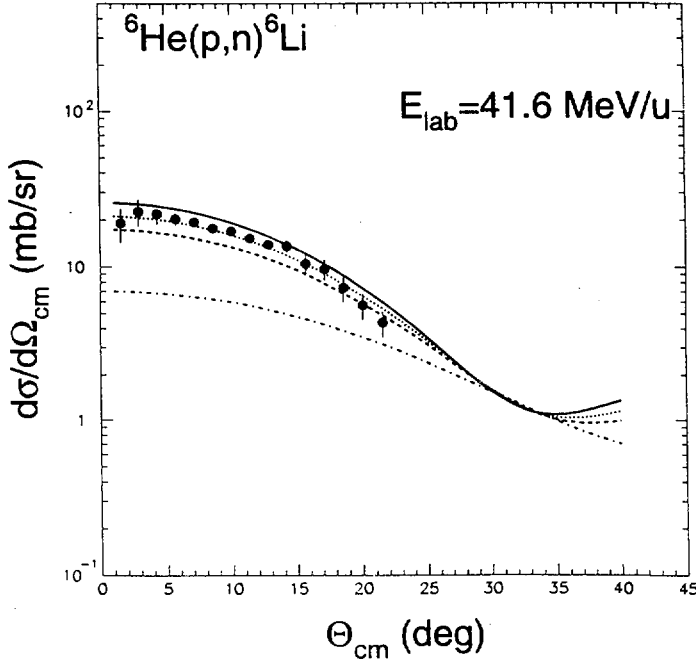


Figure 2: Comparison of the present (p,n) results and JLM calculations ($\lambda v=1$, $\lambda w=1.8$) assuming different density distributions. See text for more details.

It is obvious that the non-halo distributions give predictions way out of our results. The other distributions give results close to the experimental values, with the best fit obtained by the two Gaussian distributions with the values obtained by Sagawa for the root mean square radii. It is interesting to note the sensitivity of the (p,n) cross sections not only to different radii but also to different shapes of the distribution. For instance the angular distributions calculated assuming a two Gaussian shape density distribution and a Hartree-Fock density distribution with the same root mean square radii differ by 20%.

In summary, angular distributions for the reaction connecting the ground state of ^6He and the ground and excited states of ^6Li have been obtained. The angular distribution leading

from the ${}^6\text{He}$ ground state to its isobaric analogue state in ${}^6\text{Li}$ was analyzed together with the $p({}^6\text{He}, {}^6\text{He})p$ elastic scattering data. A consistent description of both angular distributions was obtained by using experimental or theoretical density distributions. Precise elastic and (p,n) charge exchange reaction measurements, extending to larger angles, may be used to investigate the shape of the density distribution or when the density distribution is known from precise high energy measurements to investigate the isoscalar and isovector part of the nucleon-nucleon interaction far from the valley of stability.

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A2 - EXOTIC NUCLEI AND DECAY MODES

Decay Spectroscopy of Neutron Rich Nuclei

GANIL E267

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Nuclei possessing neutron/proton ratios radically larger than those of stable isotopes exhibit unexpected phenomena which have revolutionised our understanding of nuclear physics. Although the neutron drip line has probably been delimited for elements below neon [1] and atomic masses of many nuclei have been measured [2], comparatively little is known about their radioactive decay characteristics or spectroscopy. Such measurements can probe important details of the underlying microscopic structures which give rise to the novel phenomena.

The neutron rich nuclei of interest were produced by the fragmentation of a 0.5 μ A 77.7A MeV beam of the rare isotope $^{36}\text{S}^{16+}$ in a range of tantalum targets mounted on carbon backings and separated using the LISE3 spectrometer [3]. The selected nuclei were implanted into a stack of six silicon detectors located at the focal plane of LISE3, which were used to provide an unambiguous identification of the ions on an event-by-event basis and to detect β -particles emitted in the radioactive decay of the implanted nuclei.

The energies of γ -rays emitted following β -decay were measured using 4 germanium detectors, each of 70 % relative efficiency, mounted in close proximity to the implantation point around 0° to the secondary beam direction. The silicon detector stack was surrounded on three sides by 42 cylindrical ^3He proportional counters, which were used to determine β -delayed neutron emission probabilities.

In these measurements it was possible for the first time to identify γ -rays emitted in the β -decays of ^{24}O , $^{25-27}\text{F}$ and $^{28-30}\text{Ne}$ and to obtain candidate γ -ray lines in another 2 cases, which will provide the basis for further investigations. The half-lives of the selected nuclei were determined from the time intervals between their arrival and subsequent β -decay, with 4 half-lives being measured for the first time. The energy level schemes deduced from these spectra, the absolute β -decay strengths feeding these levels and the half-lives are being compared with shell model calculations in order to learn more about the structure of nuclei in this region.

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Study of neutron-rich nuclei near the N=20 neutron closed shell

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An interesting aspect of the region of N=20 nuclei is the transition from spherical to deformed shapes in the so-called “island of inversion”. The deformations in this region can also result in the appearance of the isomeric states of extremely neutron-rich isotopes. Such effects may influence the decay properties of these nuclei, such as half-life, neutron emission probability. The lack of experimental information on the very neutron-rich isotopes in the C-Al region is mainly due to the very low production cross section. Therefore a very exotic primary beam of ³⁶S (78 AMeV) ions, which give an opportunity to study the β -delayed neutron emission from neutron-rich nuclei with the magic neutron number N=20, such as ²⁹F, ³⁰Ne and ³¹Na, was used in the experiment. The experiment was carried out at GANIL using the Si(Li) detectors telescope at the focal point. The implantation detectors were surrounded by 3He filled neutron detectors. This detector system was served as both the fragment identification and β -delayed neutron decay measurement. For the first time the β -decay half-lives and neutron emission probability were measured for ³⁰Ne, ^{26,27,29}F. Additionally, the cases of ²²N, ²⁴O, ²⁴⁻²⁹Ne, ²⁵F, ^{30,32}Na were re-examined (see Table) [1].

The measured half-lives for ²⁸Ne and ^{30,31}Na agree within the error bars with the previous experiments. The only important discrepancy is observed for ²⁹Ne. The experimental half-lives obtained here are in good agreement (within a factor of two) with the sd shell-model calculations of Wildenthal et al. [2] including the values for ^{27,29}F and ^{29,30}Ne. The last suggest that the deformation phenomena, predicted and observed in the Mg - Na region, disappears below Z=11. Thus the standard shell-model space seems to be sufficient to predict half-lives of fluorine and neon isotopes in vicinity of N=20.

The attempt to synthesize ^{28}O was carried out at GANIL using the LISE spectrometer, which collects projectile-like fragments. The fragmentation of a $^{36}\text{S}^{16+}$ (78.1 AMeV) beam with a mean intensity 800 enA was expected to increase the production rate of the neutron-rich isotopes near $N=20$. Measurements of the momentum distributions of all fragments with $N=20$ and an optimization of the target material (Be, C, Ni, Ta) and thickness were undertaken to determine the best setting of the LISE spectrometer for ^{28}O . It was found that the Ta target produced the highest rates of the neutron-rich nuclei.

During 53-hours measurement with this average beam intensity no events corresponding to ^{26}O and ^{28}O have been obtained. In the addition to A/q and Z identification, a horizontal coordinate in the intermediate dispersive plane of the LISE spectrometer was in agreement with the computer simulation of horizontal images in the focal point. According to the estimation given by the modified formula of Summerer et al. [2] one could expect about 11 events corresponding to ^{28}O .

The results of the present experiment point to the particle instability of the ^{28}O isotope as well as for ^{26}O . An upper limit for the cross section of the formation of the oxygen isotopes extracted from the data is estimated to be 0.7 pb and 0.2 pb for ^{26}O and ^{28}O , respectively.

Table. Experimental values of the β -decay half-lives and neutron emission probability of neutron-rich nuclei close to $N=20$

Isotope	Experimental results			
	This work		Table of Isotopes 1996	
	$T_{1/2}$ ms	P_n %	$T_{1/2}$ ms	P_n %
^{22}N	31 (5)	37 (14)	24 (7)	35 (5)
^{24}O	67 (10)	12 (8)	61 (26)	58 (12)
^{25}F	70 (10)	14 (5)	59 (4)	15 (10)
^{27}F	9.6 (0.8)	11 (4)		
^{29}F	2.4 (0.8)	100 (80)		
^{27}Ne	22 (6)	0 (3)	32 (2)	2 (0.5)
^{28}Ne	20 (3)	11 (3)	17 (4)	22 (3)
^{29}Ne	15 (3)	27 (9)	200 (10)	
^{30}Ne	7 (2)	9 (17)		
^{30}Na	50 (4)			
^{31}Na	18 (2)		48 (2)	30 (4)

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Beta decay half-lives of neutron rich Ti-Co isotopes around N=40

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The present work is a continuation of that presented in in ref. [1]. The isotopes ^{57–59}Ti, ^{59–62}V, ^{61–64}Cr, ^{62–66}Mn, ^{65–68}Fe, ^{67–70}Co were produced from the fragmentation of a ⁸⁶Kr 60,4 MeV/u beam impinging onto a Ni(140 μ m)+C(9,5 mg/cm²) target. The primary beam intensity was on average 1.2 μ A. A wedge-shape Be foil of 219 μ m-thickness was placed in the intermediate focal plane of the LISE3 spectrometer in order to reduce the rate of contaminant nuclei. Two different magnetic settings were used to transmit nuclei with increasing neutron richness. B ρ -values of 2.6730 Tm and 2.7268 Tm were chosen in the first part of the spectrometer. Selected nuclei were identified in redundant way by means of 4 consecutive 300, 300, 500, 500 μ m silicon detectors placed close to the final focal plane. Fragments were implanted in the last detector divided in twelve 2mm-wide vertical strips. Energy and time of each fragment and each β -particle were registred in the strips of interest. Each time a nucleus was implanted, the primary beam was switched off during 1.5 seconds, a duration long enough for the decay of the mother and daughter nuclei. All β -particles detected during this time are taken into account for half-life determination. A β -particle is accepted as an event coming from the β -decay of the implanted isotope if it is above the background of a given strip and detected in the same strip or in neighbouring strips as the precursor. Other β -events are counted as β -background. This background presents a period of 4.7 ± 0.5 s and 5.3 ± 0.1 s for the two explored tunings of the spectrometer coming from decays of long-lived nuclei. Background frequency values of less than 0.05 β -particles per second were obtained for each strip. The β -efficiency was found around 15 %. Preliminary results are given in Table 1.

The deduced Fe and Co half-lives are compatible with the values obtained at GSI [2] except for ⁷⁰Co and ⁶⁵Fe. The decay curve of ⁶⁵Fe, almost flat, can be reproduced only if the ⁶⁵Fe half-life is close to the half-life of the ⁶⁵Co daughter nucleus. This excludes to deduce a value as short as the one measured at GSI [2, 5]. To determine the ⁶⁵Mn half-life, our value of ⁶⁵Fe half-life (1317(279) ms) was used to fix the daughter nucleus half-life parameter. A value of 100(8) ms was found, between the values of ref. [2] and [7]. With a daughter half-life parameter of 800 ms, a value of 88(8) ms would be deduced. In ^{64,66}Mn isotopes, our values are shorter than those published in ref. [2] but are in very good agreement with those measured at CERN/Isolde [7].

The measured Cr half-lives are close to those of ref. [2]. For ^{61–62}Cr the decay curves were fitted using the known half-lives of the ^{61–62}Mn daughter nuclei. For ⁶³Cr, our ⁶³Mn half-life value was taken into account. The ⁶²Cr decay curve cannot be fitted using the known ⁶²Mn half-life of 880(150) ms ; the fit requires a much shorter value of 80(15) ms. The beta-decay may occur to a ⁶²Mn isomeric state which decays to the ⁶²Fe with an half-life of 80(15) ms. The ⁶⁴Cr half-life is found much smaller than the one of ⁶³Cr in contradiction with the prediction

of Möller (96.6 et 153.9 ms for ^{63}Cr and ^{64}Cr respectively with deformation parameter of 0.3 et 0.017 [8]).

In addition to the implantation set-up, 4 germanium detectors were placed in cross geometry around the last Si detector in order to detect the main γ transitions. In the decay of ^{60}V a strong transition was observed for the first time at 646.3(1.5) KeV which probably corresponds to the $2^+ \rightarrow 0^+$ transition in ^{60}Cr . This energy is smaller than the 2^+ -energy of the isotone ^{62}Fe measured at 878.6(1.5) KeV in decay of the ^{62}Mn . We found that the decay of ^{64}Mn feeds the 2^+ -level of the ^{64}Fe at 745.5(1.5) KeV. This shows the decrease of the 2^+ -energy in the Fe towards N=40 and the weakening of this shell strength.

Isotope	N	$T_{1/2}(\text{ms})$	$T_{1/2}(\text{ms})$ (previous measurements)
^{57}Ti	125	67(25)	180(30)[2], 56(20)[1]
^{58}Ti	286	47(10)	
^{59}Ti	86	58(17)	
^{59}V	2306	75(7)	130(20)[2], 70(40)[1] 200(40)[2]
^{60}V	1042	122(18)	
^{61}V	776	43(7)	
^{62}V	51	65(31)	
^{61}Cr	4455	251(22)	270(20)[2] 190(30)[2] 110(70)[2]
^{62}Cr	2771	187(15)	
^{63}Cr	835	115(16)	
^{64}Cr	215	44(12)	
^{63}Mn	7966	322(23)	240(30)[3], 250(40)[6], 275(4)[7] 140(30)[2], 89(4)[7] 110(20)[2], 88(4)[7] 90(20)[2], 66(4)[7]
^{64}Mn	7348	85(5)	
^{65}Mn	3226	100(8)	
^{66}Mn	400	62(14)	
^{65}Fe	3541	1317(279)	600(100)[3], 450(150)[5] 440(60)[2] 470(50)[2]
^{66}Fe	3541	440(60)	
^{67}Fe	2820	500(98)	
^{67}Co	805	436(77)	370(100)[3], 420(70)[6] 230(20)[3], 180(100)[4] 270(50)[4] 150(20)[2]
^{68}Co	597	170(30)	
^{69}Co	1961	187(38)	
^{70}Co	259	92(25)	

Table 1: Half-life values compared to previous measurements. N is the number of implanted isotopes.

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Beta-decay studies of the neutron-rich isotopes $^{53-55}\text{Sc}$, $^{54-57}\text{Ti}$, $^{56-59}\text{V}$.

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The very short half-life of $T_{1/2}=90\pm15\text{ms}$ compared to the neighbouring isotopes ^{52}Ca ($T_{1/2}=4.6\pm0.3\text{s}$) [1] is due to strong Gamow-Teller transition in the β -decay of $^{53}\text{Ca}_{33}$. This effect suggests a rather strong subshell gap at a neutron number $N=32$ which is confirmed by the large energy of the first 2^+ -state in $^{52}\text{Ca}_{32}$ ($E=2.563\text{ MeV}$) [2]. It is therefore of interest to investigate the decay of the neighbouring $N=33$ isotones ^{54}Sc , ^{55}Ti and ^{56}V in order to check whether this spherical gap subsists when adding protons to the calcium nucleus. The isotopes $^{53-55}\text{Sc}$, $^{54-57}\text{Ti}$ and $^{56-59}\text{V}$ were produced by fragmentation of a 64.5 MeV/u ^{65}Cu beam impinging onto a 90 mg/cm^2 Be target. An aluminum wedge-degrader of $221.5\text{ }\mu\text{m}$ -thickness was placed in the intermediate focal plane of the LISE3 spectrometer in order to reduce the rate of contaminant nuclei. The WIEN-type velocity filter of LISE3 was used in addition to eliminate long-lived nuclei, which would have enhanced the β -background. Nuclei selected were identified by means of two consecutive $300\text{-}\mu\text{m}$ and $500\text{-}\mu\text{m}$ silicon detectors. The nuclei were implanted in the second Si-detector, consisting of twelve 2mm -wide strips ($24\times2\times0.5\text{ mm}$). The energies and times for the heavy ions and for the β -particles were measured in each strip. A β -event was only recorded as valid if occurring in the same strip as the precursor nucleus or in one of the neighbouring strips. In addition, each time a nucleus was implanted, the primary beam was switched off for about five times its expected β -half-life in order not to implant contaminant nuclei during the β -measurement. The Si telescope was surrounded by a 4π γ -detection system, composed of a ring of 8 BGO crystals. This system allowed a very high β - γ coincidence efficiency, $\varepsilon_{\beta}\times\varepsilon_{\gamma}\approx0.25\times0.66$, ε_{β} and ε_{γ} being the average total β - and γ -efficiencies respectively. The BGO detectors also allowed to investigate the strongest γ -transitions. Energy levels could be tentatively assigned with a resolution of 18%. Adopted values of the half-lives from ref [3,4] are included in the Table 2. The QRPA model of Möller and Randrup [5] has been used to calculate GT-strength functions and β -decay half-lives. In this approach, Folded Yukawa (FY) wave functions and single-particle energies serve as a starting point to determine

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the deformation-dependent wave functions. Experimental data are compared with QRPA predictions in ref. [4] in order to get the "best possible agreement" and thus learn something about the underlying nuclear structure.

Table 1: Measured half-lives for Sc^[4], Ti^[3] and V^[4]. The number of nuclei implanted is indicated in the second column

isotope	total	T _{1/2} [ms]
⁵³ Sc	682	> 3000
⁵⁴ Sc	363	225(40)
⁵⁵ Sc	42	120(40)
⁵⁴ Ti	1729	1500 (400)
⁵⁵ Ti	3523	620 (60)
⁵⁶ Ti	1531	150 (30)
⁵⁷ Ti	40	56 (20)
⁵⁶ V	1746	230(25)
⁵⁷ V	3189	323(30)
⁵⁸ V	1347	205(20)
⁵⁹ V	55	70(40)

This can be done by varying the deformation parameter ϵ_2 within and slightly beyond the model predictions in this mass region suggested by FRDM [6] and ETFSI [7] models. The Lipkin-Nogami approximation is applied to calculate pairing correlations. In some cases, the measured probability p of feeding excited states, or $p_{g.s.} = 1-p$ to populate the ground state (g.s.), can be used as a constraint on the deformation. For example, in the case of ⁵⁴Sc, the experiment has shown that all decay is followed by a gamma emission ($p \geq 100\%$). For a spherical configuration, one would expect a strong $\nu f_{5/2} \rightarrow \pi f_{7/2}$ GT-transition g.s. to g.s. transition ($p=0\%$) and a short half-life of $T_{1/2} = 14$ ms. The long measured half-life $T_{1/2} = 225 \pm 40$ ms, and the high probability of feeding excited states can be obtained for a deformed shape of $\epsilon_2=0.15$ and a g.s. configuration of $\pi[330]1/2 \otimes \nu[312]3/2$. Similar conclusions can be drawn for Ti and V isotopes, pointing towards a region of slightly

prolate shapes. Therefore, one can conclude that this subshell closure is only present for ⁵²Ca isotope. Indeed for this $Z=20$ isotope, the configuration mixing is very small, probably due to the magic proton-number that hinders any deformation.

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A mass measurement experiment to investigate the shell closures far from stability

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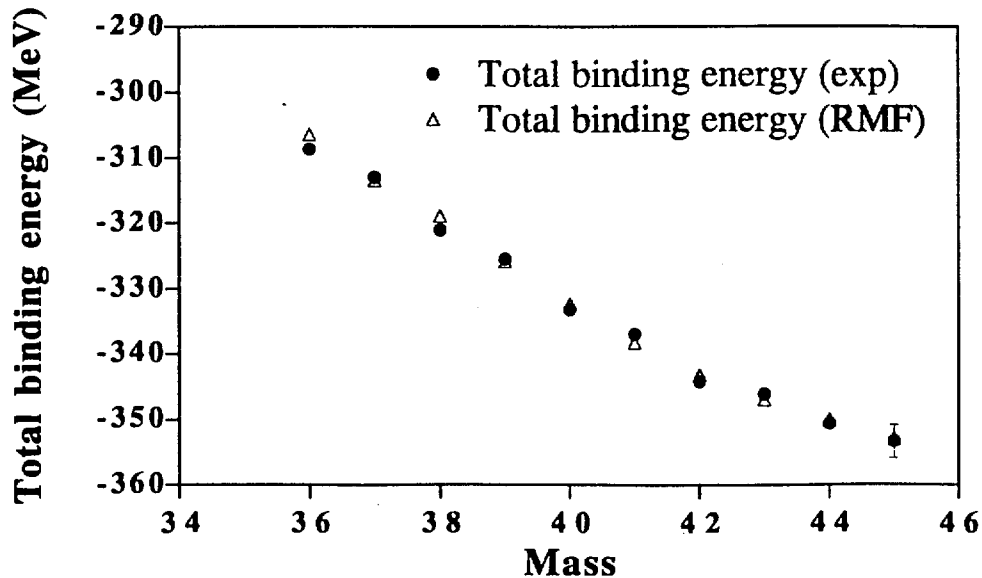
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One of the present fundamental question for nuclear structure is whether the magic numbers are universal or whether they change in certain regions far from stability or even disappear altogether. An example of such magicity breaking is given by the N=20 neutron rich nuclei where a collapse of the standard N=20 shell closure has been observed. Recently, there has been an increase of interest in the N=28 isotones far from stability, motivated by the possible existence of anomalies in the shell closures.

An experimental observable that may give a first answer to this question is the binding energy which can be deduced from nuclear masses. We have performed at GANIL a mass measurement experiment with the SPEG spectrometer by using a direct time of flight technique. Our goal was to investigate the N=20 and N=28 neutron shell closures for nuclei from Z=6 to Z=20. The production of these neutron-rich nuclei have been obtained by the fragmentation of a ⁴⁸Ca primary beam at 60 A.MeV on a Ta target located in the SSSI device.

Among the N=28 isotones, the ⁴⁴S is a nucleus having a mid-shell proton configuration. A previous experiment [1] showed that this nucleus is deformed which can be a signature of a new region of deformation even for the N=28 magic number. The mass of this nucleus have been measured for the first time with an error of less than 500 keV [2]. We performed a Relativistic Mean Field (RMF) calculation for the sulfur isotopes and we found an excellent agreement with the experimental binding energy, as it is shown in the figure, and with the deformation parameter β_2 .



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Observation of the $Z=N+1$ Nuclei $^{77}_{39}\text{Y}$, $^{79}_{40}\text{Zr}$ and $^{83}_{42}\text{Mo}$

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The very neutron deficient $Z=N+1$ nuclei $^{77}_{39}\text{Y}$, $^{79}_{40}\text{Zr}$, and $^{83}_{42}\text{Mo}$ have been observed for the first time following the fragmentation of a ^{92}Mo beam. In contrast, no evidence was found for the existence of $^{81}_{41}\text{Nb}$ and $^{85}_{43}\text{Tc}$. The observation of $^{77}_{39}\text{Y}$ is of particular interest in light of the instability of the odd-proton, $Z=N+1$ systems, $^{69}_{35}\text{Br}$, $^{73}_{37}\text{Rb}$, $^{81}_{41}\text{Nb}$, and $^{85}_{43}\text{Tc}$ and may be explained as a consequence of the shape polarising effect of the highly deformed, prolate $Z=N=38$ core.

Nuclei with nearly equal proton and neutron numbers in the $A\sim 80$ region are of fundamental interest for two distinct reasons. Firstly, the nuclear structure properties of these nuclei are strongly determined by deformed shell gaps in the nuclear single particle potential [1], which causes dramatic changes of shape with the addition or removal of one or two nucleons [2,3]. In particular, the nucleon numbers 36 and 38 have been identified with highly deformed oblate [4] and prolate [2,5] shell gaps, respectively. Secondly, these systems lie in the vicinity of the proton drip line, the precise position of which is a vital element in determining the path of the postulated astrophysical rapid proton (rp) process of nucleosynthesis [6]. The single particle spectrum of orbitals which lie close to the proton and neutron Fermi surfaces varies considerably with deformation, and this nuclear structure aspect can have a subtle, but important effect on the binding energies of odd-proton nuclei and the position of the proton drip line.

Discrepancies in the predictions of mass models [7-9] regarding the proton stability of odd- Z , $T_z = -1/2$ nuclei and their bearing on the path or termination of the rp process have prompted searches for the existence and studies of the decay properties of the $Z=N+1$ systems $^{65}_{33}\text{As}$, $^{69}_{35}\text{Br}$, $^{73}_{37}\text{Rb}$ and $^{77}_{39}\text{Y}$. Whereas the nucleus $^{65}_{33}\text{As}$ has been observed and its basic decay properties studied [10,11], the heavier odd- Z $T_z = -1/2$ nuclei were not observed in fragmentation reactions. However, there is evidence that, as the $T_z = -1/2$, odd- Z nuclei become more spherical with increasing Z - due to the increasing influence of the $N=Z=50$ doubly magic core - the population of higher- l orbitals may increase the binding and the centrifugal barrier for the odd proton. Indeed, Rykaczewski *et al.* [12] have observed $^{89}_{45}\text{Rh}$, which constitutes the heaviest odd- Z , $T_z = -1/2$ nucleus identified to date.

In the present work, evidence for the particle stability of three isotopes with $Z=N+1$, namely $^{77}_{39}\text{Y}$, $^{79}_{40}\text{Zr}$ and $^{83}_{42}\text{Mo}$, together with upper limits for the lifetimes of $^{81}_{41}\text{Nb}$ and $^{85}_{43}\text{Tc}$ are presented. The nuclei were produced in the fragmentation of a $^{92}\text{Mo}^{37+}$ beam of 60 MeV/nucleon provided by the GANIL facility. The primary beam, of typical intensity 100 enA, was incident on a 50 - 100 mg/cm² natural nickel targets. The reaction products were collected and separated using the LISE3 spectrometer [13]. At the final focus of the spectrometer, the fragments were stopped in a four-element silicon detector telescope, the first element of which was acted as an energy-loss (ΔE) detector. A time-of-flight (TOF) measurement together with the energy-loss and total-energy measurement was used to obtain an unambiguous identification in Z , N and Q for each fragment. Figure 1a shows a two-dimensional spectrum of the atomic number Z determined from the energy loss in the ΔE detectors versus the A/Z ratio determined from the fragment TOF. The projections of the $T_z = 0$ and $-1/2$ species onto the Z axis are presented in figures 1b,c and clearly show the presence of the even- Z , $Z=N+1$ nuclei, $^{75}_{38}\text{Sr}$, $^{79}_{40}\text{Zr}$ and $^{83}_{42}\text{Mo}$ in our spectra. Evidence for the existence of $^{75}_{38}\text{Sr}$ has been previously reported [10]. Tentative indication for the existence of $^{79}_{40}\text{Zr}$ has been presented previously by Yennello *et al.* [14]. This isotope is clearly present in the spectrum of figure 1c. Both $^{79}_{40}\text{Zr}$ and $^{83}_{42}\text{Mo}$ are predicted by the mass evaluation of Audi and Wapstra [7] to be proton bound, with proton separation energies of approximately 1.9 MeV and 1.2 MeV, respectively.

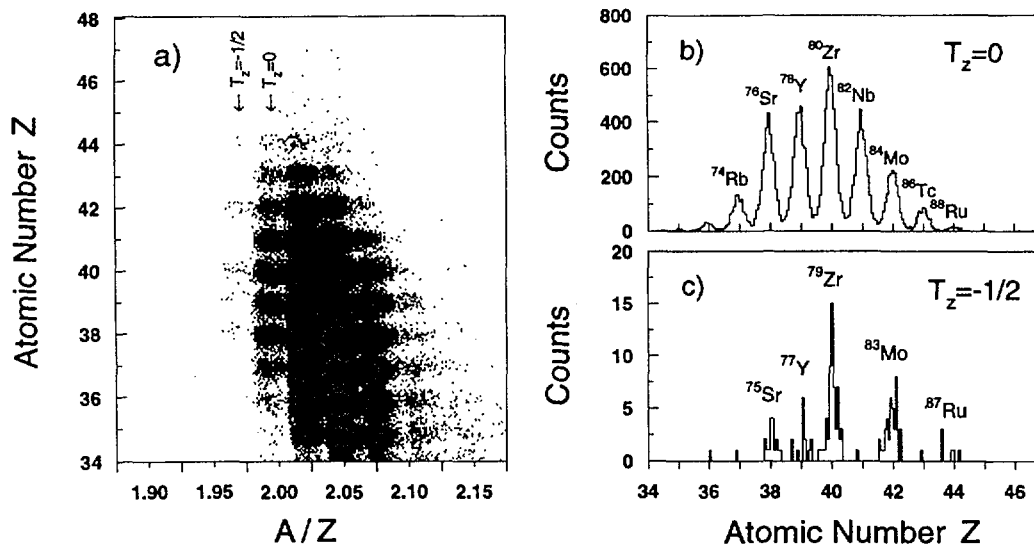


FIG. 1. Two-dimensional atomic number Z versus A/Z ratio particle identification plot showing the previously unobserved $T_z = -1/2$ nuclei $^{77}_{39}\text{Y}$, $^{79}_{40}\text{Zr}$ and $^{83}_{42}\text{Mo}$ as well as the absence of $^{81}_{41}\text{Nb}$ and $^{85}_{43}\text{Tc}$ (a). The right-hand side shows projections of the particle identification plot onto the Z axis for the $T_z = 0$ (b) and the $T_z = -1/2$ (c).

For even- Z nuclei, the pairing between the protons provides extra binding and these nuclei are expected to extend further beyond the $N=Z$ line than odd- Z nuclei. Thus, in common with previous studies [10,15,16], the current data show no evidence for $^{73}_{37}\text{Rb}$. Moreover, as demonstrated in figure 1c, we found no evidence for the odd-proton nuclei $^{81}_{41}\text{Nb}$ and $^{85}_{43}\text{Tc}$, indicating that these nuclei are proton unbound and that their lifetimes are short compared to the time of flight through the spectrometer. Assuming the observation limit of one count and considering the yields expected relative to the neighboring isotopes, we derived upper limits of 80 and 100 ns for the half-lives of ^{81}Nb and ^{85}Tc , respectively. In the region expected for $^{77}_{39}\text{Y}$, figure 1c clearly shows a peak indicating that the half-life of this isotope is longer than $0.5\ \mu\text{s}$, the flight time through the LISE3 spectrometer. Qualitatively, this observation is consistent with the proton separation energies predicted by Audi and Wapstra [7] which suggest that ^{77}Y is the most bound of the odd- Z , $T_z = -1/2$ nuclei in this region. The observation of $^{77}_{39}\text{Y}$ may be interpreted as evidence for the shape polarising effect of the $N=Z=38$ prolate shell gap, as predicted by the macroscopic-microscopic calculations. Future decay studies of ^{77}Y which would determine spin and parity of the ground state would thus be of interest in either supporting or contradicting this assumption. Such studies should also be able to establish whether or not this isotope is particle bound via observation of the decay mode - β^+ (predicted β -decay half-life $T_{1/2}^\beta = 190\ \text{ms}$ [17]) or direct proton emission, which should be more probable if the proton decay energy is larger than 380 keV.

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HALF-LIVES OF HEAVY ODD-ODD $N=Z$ NUCLEI SELECTED WITH THE LISE3 SPECTROMETER

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The β^+ -decay half-lives of the neutron-deficient, odd-odd, $N=Z$ nuclei ^{74}Rb , ^{78}Y , ^{82}Nb and ^{86}Tc have been measured following the fragmentation of a primary ^{92}Mo beam at an energy of 60 MeV per nucleon. The half-lives were measured by correlating β^+ decays with the implantation of unambiguously identified fragments. The deduced $\log ft$ values are consistent with superallowed transitions and the transitions observed may be of Fermi type.

The half-life of a nucleus is a fundamental property of a radioactive species. This value depends on the initial and the final nuclear state wavefunction as well as of the interaction which mediates the decay : Fermi or Gamow-Teller. Fundamental aspects of the weak interaction can be studied with basic ingredients such as half-lives and β^+ -decay energies. Specific nuclear structure features can be tested. The technique of projectile fragmentation of medium-mass heavy ions, as used with the LISE/GANIL facility, and the time correlated β decay after implantation has provided an efficient method for the measurement of the fast Fermi-type decays in the heavy odd-odd, $N=Z$ systems, ^{74}Rb , ^{78}Y , ^{82}Nb and ^{86}Tc .

The nuclei of interest were produced at GANIL by the fragmentation of a $^{92}\text{Mo}^{37+}$ beam of energy of 60 MeV per nucleon with an average current of 200 enA on a natural nickel target of thickness 120 μm . The fragmentation products were separated using the LISE3 spectrometer [1] with an achromatic beryllium degrader of thickness 50 μm . At the final focus, the fragments were stopped in a three element telescope, the first element of which consisted of a 300 μm thick energy loss (ΔE) silicon detector for element (Z) identification. The ions of interest were stopped in a twelve-strip segmented silicon detector of thickness 500 μm situated behind the ΔE detector. A third silicon detector, also of thickness 500 μm , was placed behind the strip detector and was used in the off-line analysis to discriminate against any contaminating lighter ions reaching the final focus. A time-of-flight (TOF) of the fragments was measured by taking the time difference between a fast signal extracted from the ΔE detector and the cyclotron radiofrequency. This TOF together with the energy loss in the ΔE detector and the magnetic rigidity of the dipole magnets in the LISE3 spectrometer was used to obtain an unambiguous identification in Z and N for each fragment, using previously described techniques [2]. After implantation of a fragment of interest, the primary beam was immediately shut-off for one second. A millisecond clock was reset each time a detected fragment caused the beam to be cut off so that each radioactivity event was labelled. Subsequent β^+ -decays were then correlated with specific implants by looking for signals during this beam-off period in the implanted strip. In the off-line analysis, software cuts were applied to a two-dimensional particle identification matrix ΔE versus TOF. This allowed the radioactivity time distributions to be obtained for specific nuclear species.

For the odd-odd, $N=Z$ systems ^{74}Rb , ^{78}Y , ^{82}Nb and ^{86}Tc , the time distributions are shown in figure 1. The half-lives of the radioactive decays were estimated by applying a least-square fit to the data with a function composed of an exponential decay plus a constant background level.

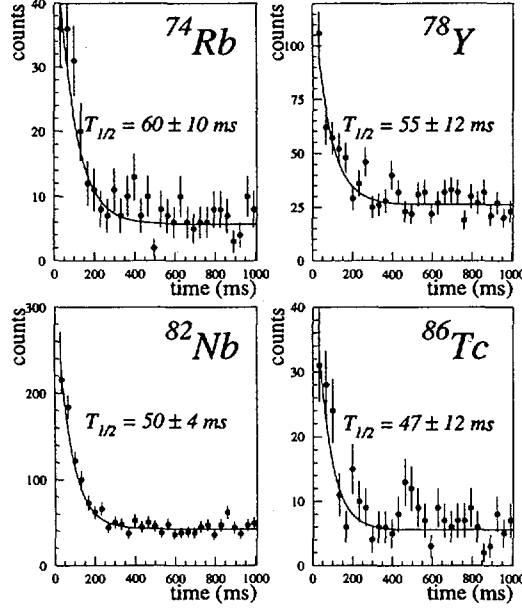


FIG. 1. Time spectra for the odd-odd $N = Z$ nuclei. The data were recorded for about 90 hours. The fit is shown by the solid line and assumes an exponential decay with a constant level background.

Our analysis yielded half-lives $T_{1/2}$ of (60 ± 10) ms for ^{74}Rb , (55 ± 12) ms for ^{78}Y , (50 ± 4) ms for ^{82}Nb , and (47 ± 12) ms for ^{86}Tc . The half-life of ^{74}Rb has previously been measured by D'Auria *et al.* [3] to be (64.9 ± 0.5) ms which is consistent with our result for this nucleus and provides a cross-check for our method. The time curves gated by the even-even, $N=Z$ nuclei in this region all showed flat time distributions indicative of decay lifetimes longer than the one second beam-off period. The $\log ft$ values for these β^+ -decays were calculated assuming i) a branching ratio of 100% for the observed transition, ii) a ground-state to ground-state decay and iii) the β^+ -decay Q values from the mass evaluation of Audi *et al.* [4]. The calculated $\log ft$ values are all compatible within error bars with $\log ft = 3.5$ which is indicative of a superallowed character for each of these decays. The question now arises what is the ground state of the odd-odd $N=Z$ nuclei ^{78}Y , ^{82}Nb and ^{86}Tc . Looking at the systematic, light nuclei, from deuteron to mass 38, have ground state $T = 0$, $I \neq 0$ and heavier nuclei have $T = 1$, $I^\pi = 0^+$ ground states. This has been shown for ^{74}Rb by recent in-beam work [5] and assumed for ^{78}Y by J. Uusitalo *et al.* [6]. We make the assumption that the ground state is $T = 1$, $I^\pi = 0^+$ for ^{78}Y , ^{82}Nb and ^{86}Tc . The daughter nuclei populated following the β^+ decay of these odd-odd, $N=Z$ systems are even-even nuclei ($T_z = 1$), and thus have 0^+ ground states. This implies that the decays observed in our studies are all of a $0^+ \rightarrow 0^+$ Fermi character.

The LISE3 spectrometer, combining electromagnetic dipoles, achromatic degrader and Wien filter, provides a clean selection and identification of nuclei produced by the fragmentation of a ^{92}Mo beam. Such a facility has allowed the first half-life measurement for the odd-odd, $N=Z$ nuclei ^{78}Y , ^{82}Nb and ^{86}Tc .

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Mass Measurements near $N=Z$ and ^{100}Sn

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Nuclei near $N=Z$ may be studied in order to determine the shell-closures, the deformations that may particularly strong and symmetries such as mirror symmetries and Wigner terms. An experiment aimed at measuring the masses of proton-rich nuclei in the mass region $A \approx 60-80$ has been performed, using a direct time-of-flight technique in conjunction with SISSI and the SPEG spectrometer at GANIL. The nuclei were produced via the fragmentation of a ^{78}Kr beam (73 MeV/nucleon). A novel technique for the purification of the secondary beams, based on the stripping of the ions and using the α and the SPEG spectrometers, was successfully checked. It allows for good selectivity without altering the beam quality. This work is described in ref. 1.

In the region $N \approx Z$ of the nuclear chart, fusion evaporation reactions are very competitive with respect to fragmentation reactions. They should be considered, too, for the preparation of Isol beams. Secondary ions of ^{100}Ag , ^{100}Cd , ^{100}In and ^{100}Sn were produced via the fusion-evaporation reaction $^{50}\text{Cr} + ^{58}\text{Ni}$ at an energy of 5.1 MeV/nucleon, and were accelerated simultaneously in the second cyclotron of GANIL (CSS2). About 10 counts were observed from the production and acceleration of $^{100}\text{Sn}^{22+}$. The masses of ^{100}Cd , ^{100}In and ^{100}Sn were measured with respect to ^{100}Ag using the CSS2 cyclotron, with precisions of 2×10^{-6} , 3×10^{-6} and 10^{-5} respectively. More details can be found in ref.2,3.

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B - NUCLEAR REACTIONS

B1 - PERIPHERAL COLLISIONS

Some regularities in the production of isotopes in $^{32,34,36}\text{S}$ - induced reactions in the energy range 6-75 A MeV

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The investigation of the mechanism of nuclear reactions is closely connected with the projects for radioactive nuclear beam facilities, which will open new possibilities for the study of exotic nuclei and which will generate radioactive secondary beams by using primary beams of very different energies. Questions arise concerning to the extent of coexistence of different reaction mechanisms (e.g. multi-nucleon transfer reactions and fragmentation) at various energies, the dependence of the production rates on the isospins, of the projectile and target etc. Some regularities in the production of the isotopes with $6 \leq Z \leq 14$ are investigated in the reactions induced by $^{32,34,36}\text{S}$ beams. The results, discussed in the present work have been obtained in a very broad range of the beam energy ($6 < E < 75$ A MeV) with various targets: ^{12}C , ^{181}Ta and ^{197}Au . The isotope yields and the most probable fragment mass are studied in relation to the mass and energy of the target and projectile. The experiments with $^{32,34}\text{S}$ beam energy were $E < 20$ A MeV carried out at the U-400 cyclotron of the Flerov Laboratory of Nuclear Reactions (JINR). The yields of the various isotopes were measured using the MSP-144 magnetic spectrometer [1]. The ^{36}S (75 A MeV) beam was provided by the GANIL accelerator facility (France); the isotope yields were measured by the LISE fragment-separator [2]. The distributions of the carbon, oxygen, neon, magnesium and silicon isotopes produced in ^{32}S and ^{34}S (6.3; 9.1 and 16 A MeV) and ^{36}S (75 A MeV) induced reactions on three targets (^{12}C , ^{181}Ta , ^{197}Au) were obtained. The experimental data at low energy were compared with the calculation within the framework of the dynamical model of deep inelastic collisions [3]. The yields of the isotopes in the intermediate energy region were calculated with the LISE-code. The isotopic distributions of the final (experimentally observed) nuclei were calculated within the framework of the statistical theory of decay of excited primary fragments. The comparison of the experimental data and the calculations shows (Fig. 1a) that the contribution of deep inelastic reactions to the production cross section of both neutron-rich and neutron-deficient isotopes is dominant at low energies (the dashed lines), while at intermediate energies the main contribution is defined by fragmentation reactions.

On the basis of the data obtained the following conclusions can be drawn:

- In the energy range 7-10 MeV/A quite an abrupt decrease in the cross section is observed in the case of a light target as the number of transferred protons increases. At high energies this difference decreases and is negligible at intermediate energies.

- At high energies the isotopic content of the projectile plays a dominant role in the production of nuclei close to the projectile ($Z \geq 12$), while at energies $E < 20$ MeV/A the production cross sections for ^{32}S and ^{34}S beams are comparable.

A difference in the cross sections is only observed in the region of nuclei heavier than the projectile, where pick-up reactions prevail.

The isotope production cross sections are seen to rise for energies up to about 15-20 MeV/A, after which they either flatten or pass through the maximum and drop in the energy regions where fragmentation is expected to prevail.

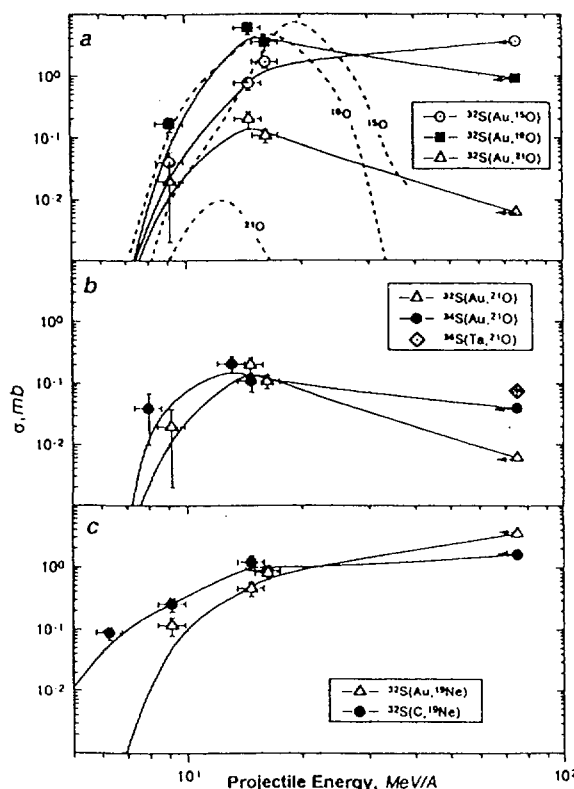


Fig. 1. Total production cross section for different isotopes as a function of energy. The solid curves are the results of the calculations using a modification of the empirical parametrization. The dashed lines present the calculations of the transfer reaction products.

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B2 - DISSIPATIVE COLLISIONS

Thermal and chemical equilibrium for vaporizing sources

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At present there exist many models, describing a simultaneous disassembly of nuclear sources produced in nucleus-nucleus collisions at intermediate energies, which presuppose that before disintegrating these sources achieve partial or complete thermodynamical equilibrium. This hypothesis is essential if one wants to describe the sources by means of macroscopic variables such as pressure and density at finite temperature. We report here on a detailed comparison of the properties of vaporized quasi-projectiles (QP) produced in binary dissipative collisions between ^{36}Ar and ^{58}Ni nuclei at 95 A MeV incident energy with a quantum statistical model. Particularly, the completeness of the selected sources made possible the extraction of variances for multiplicities of the different emitted charged particles, thus permitting a more stringent comparison with the model. Apart from the completeness of information, these sources are also interesting because they represent an extreme deexcitation mode for hot pieces of nuclear matter, close to the intuitive expectation of a supercritical nuclear gas. The vaporization events, which correspond to a cross section corrected for efficiency of 1 mb [1], were shown to result mainly (about 90%) from binary dissipative collisions providing us with a well defined set of sources covering a broad range in excitation energy (ϵ^*), from 8 to 28 A MeV for the QP [2].

In the model [4] the emitting source is supposed to undergo a simultaneous disassembly at fixed temperature T , density ρ and isospin (N/Z) into a gas of fermions and bosons in thermal and also chemical equilibrium [5]. Calculations are performed within the grand canonical ensemble. Corrections to an ideal gas are included in the form of excluded volume effects in the spirit of the Van der Waals gas to deal with collisions and reabsorption at freeze-out [4]. The consequence of the excluded volume is to favour protons, neutrons and alphas over the more loosely bound structures like deuterons and high-lying resonances. Finally the calculated distributions are corrected for the side-feeding of resonance decays. A Metropolis event generator is here introduced to extend

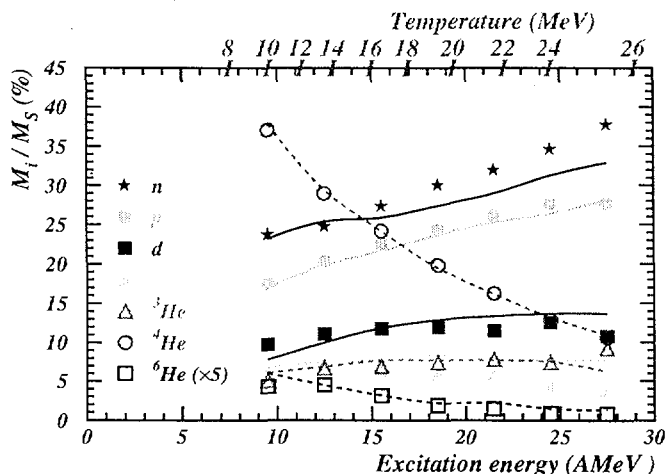


Figure 1: Composition of the QP as a function of its excitation energy. Symbols are for data while the lines are the results of the model. The temperature values used in the model are also given (see text).

the comparison of ref. [3] to the second moment of the multiplicity distributions. To cover

the experimental ε^* range the temperature had to be varied from 10 to 25 MeV. Isospin (N/Z) was fixed to 1, which is very close to the N/Z of the system. Finally the freeze-out density has been fixed to $\rho = \rho_0/3$, in order to reproduce the experimental ratio between the proton and alpha yields at $\varepsilon^*=18.5$ MeV calculated from the Metropolis simulation. Fig 1 exhibits the evolution of the relative particle abundance M_i/M_s where M_s is the total source multiplicity. The results of the model correspond to lines in Fig 1. Chemical compositions (first moments) as a function of the excitation energy are very well reproduced. Two elements were found essential to get such an agreement. First, the excluded volume correction which was already used in [3]. And second, the extension of the mass table which has been used here (only species up to 9B were included in the partition sum of ref. [3]). As compared to ref. [3], neutron, triton and 3He relative abundances are better reproduced. The comparison data-calculations is displayed in Fig 2 for the variances

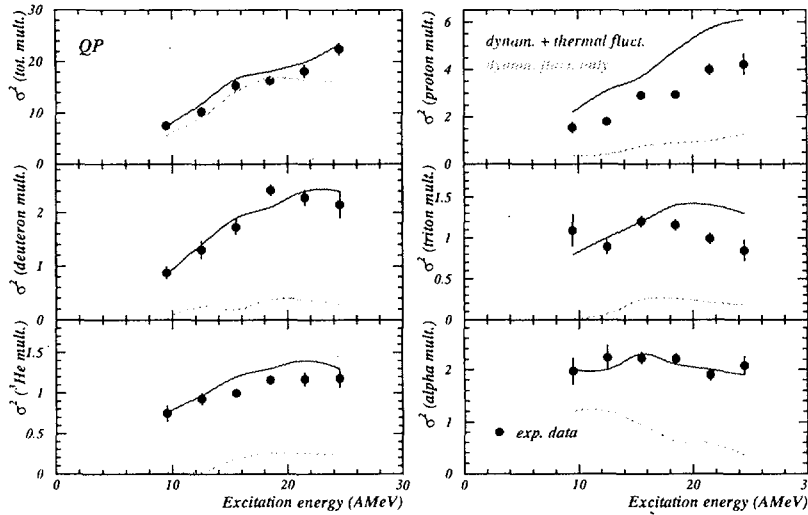


Figure 2: Variances of multiplicity distributions (total, proton, deuteron, triton, 3He and alpha) of the QP as a function of its excitation energy per nucleon. Points refer to the data and the lines are the results of the model (see text). Error bars are statistical errors

associated with the total multiplicity and with the different charged particle multiplicities. The order of magnitude is correctly reproduced by the calculation, as well as the evolution with the excitation energy. The thermal origin of the observed fluctuations is confirmed by a simulation (dashed curves) where only the fluctuations coming from the event selection criteria and/or from the dynamics of the reaction are taken into account and thermal fluctuations are frozen. As expected only variances on the total multiplicity are reproduced in this latter case while the fluctuations observed for the different particles are very small compared to experimental values. The correct prediction of the measured variances validates the value of the freeze-out density fixed in the model and reinforces the idea that thermodynamical equilibrium has been reached.

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Energy Sharing in binary collisions

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Abstract

Using the 4π multidetector array INDRA at GANIL, we have investigated the reaction $^{36}_{18}\text{Ar} + ^{58}_{28}\text{Ni}$ for bombarding energies ranging from 52 to 95 MeV/A. Over this energy domain, binary dissipative collisions are the dominant process [1, 2]. The emission sources have been reconstructed from the charged particles emitted in the forward and the backward hemispheres of the center of mass frame. The deposited energy deduced from calorimetry of the decay products is shared equally between the quasi-projectile and the quasi-target suggesting that the thermal equilibrium between the two partners is not achieved.

In order to reconstruct the primary sources from the kinematical properties of the detected charged particles we have developed an event-by-event method based on the “minimum spanning tree” technique [3, 4]. This consists in finding the minimum path linking the particles in the velocity space and break the branch of the tree which maximizes the source separation. The average charge of the reconstructed quasi-projectile ($Z_{QP} \approx 16$) and quasi-target ($Z_{QT} \approx 24$), obtained at 95 MeV/A, are very close to the expected value taking into account the detection efficiency.

Knowing the center-of-mass of the two emitters, the deposited energy ($\varepsilon_s = E_s^*/A_s$) is determined through the calorimetry of the charged particles (E_i : kinetic energy, m_i mass):

$$E_s^* = \sum_{i=1}^{M_{tot}} (E_i + m_i) + M_n (< E_n > + m_n) - m_s$$

Some assumptions must be done for neutrons which are not detected by the experimental setup. On the one hand, the neutron multiplicity (M_n) is deduced from mass and isospin conservation. On the other hand, the neutron energy ($< E_n >$) is taken as the mean kinetic energy of protons minus 2 MeV due to the absence of Coulomb barrier.

In order to follow the evolution of the deposited energy into the quasi-projectile (ε_{QP}) and the quasi-target (ε_{QT}) with the violence of the collision, we have considered only well characterized events in momentum (at least 65% of the projectile momentum). This selection allows to explore the lowest dissipative collisions for which the target-like-fragment (TLF) is not detected. Some assumptions about the charge and the momentum of the TLF are needed to complete these events. First of all, we assume that only one fragment is missing, confirmed by the simulations [5] filtered with the INDRA response function. The TLF charge is deduced from charge conservation taking into account the INDRA efficiency (90% of 4π). The TLF velocity is related to the PLF one by the formula: $V_{TLF} = \frac{M_{proj}}{M_{targ}}(V_{proj} - V_{PLF})$.

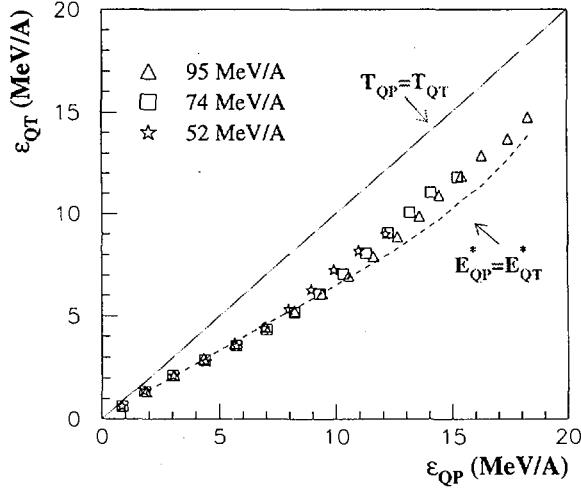


Figure 1

Correlation between the energy deposited into the Quasi-Projectile and the Quasi-Target as a function of the degree of dissipation (see text).

The events are sorted according to the energy deposited into the system ($\frac{E_{QP}^* + E_{QT}^*}{A_{QP} + A_{QT}}$). The correlation between the excitation energy imparted to the two interacting partners, plotted in fig. 1, shows that the thermal equilibrium given by the solid line is not reached. The mean QP temperature remains higher than the QT one for the overall dissipation range. The data suggest rather an equal energy sharing given by the dashed line. This trend is compatible with short interaction times as predicted by dynamical calculations ($\tau_{int} \approx 50 - 80$ fm/c) [6].

Some deviations occur at high excitation energy ($\varepsilon > 12$ MeV/A) which are due to variations in source sizes. In central collisions, the overlap of the two partners is broad. Therefore the decay products at mid-rapidity are distributed in a symmetrical way into the QP and the QT and induce the rise towards the thermal equilibrium which could be meaningless.

The study of the binary collisions observed in the $^{36}\text{Ar} + ^{58}\text{Ni}$ reactions has shown that beyond 52 MeV/A the deposited energy is equally shared between the quasi-projectile and the quasi-target for the overall dissipation range. This result is inconsistent with a full thermalization of the system even for the central collisions where 80% of the available energy is damped in the exit channel.

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Chemical and kinematical properties of mid-rapidity emissions in Ar+Ni collisions from 52 to 95 A.MeV.

T. Lefort, D. Doré, D. Cussol, J. Péter, for the INDRA collaboration.

The study of particles emitted around mid-rapidity can provide information on the first moments of the collision. At intermediate energies (between 30 and 100 A.MeV), a transition between low energy deep inelastic collision processes to the high energy participant-spectator scenario has been observed. This reflects the increasing role of individual nucleon-nucleon collisions relative to the collective mean-field when the beam energy increases. Dynamical calculations have shown that the particles are emitted at different times. One question is then: is it possible experimentally to have access to the different collision times by looking at the rapidity distributions of light particles ?

The study presented here has been performed on the $^{36}\text{Ar} + ^{58}\text{Ni}$ system from 52 to 95 A.MeV. This experiment has been done with the 4π INDRA detector. Events have been sorted in impact parameter b_{exp} following their total transverse energy E_{trans} .

The rapidity distributions of light charged particles and their mean transverse energies are not reproduced by a simulation assuming only a statistical decay from a quasi-target and a quasi-projectile. Additional contributions located around mid-rapidity (labelled MRE) are needed to explain the data [1, 2].

In order to quantify the MRE, three methods have been used: two based on the shapes of the rapidity distributions [1] and one based on the kinetic energy spectra (three source fit analysis labelled TSF) [2]. Figure 1 shows the evolution of the total MRE mass with b_{exp} for 52 (full circles), 74 (open squares) and 92 (full triangles) A.MeV. The right hand scale of this figure corresponds to the relative amount (in percent) of MRE relative to the projectile mass.

It is clearly seen that MRE mass is weakly dependent on the beam energy, but strongly depends on b_{exp} . The same observations are made on the particle multiplicities.

One observable to check the energetic properties of MRE is the double ratio parameter DRP obtained from the isotopic ratios as proposed by S.Albergo. The result of this analysis is shown in figure 2 for four different isotopic ratios. The independence with respect to the violence of the collision and the dependence on the beam energy are observed. The

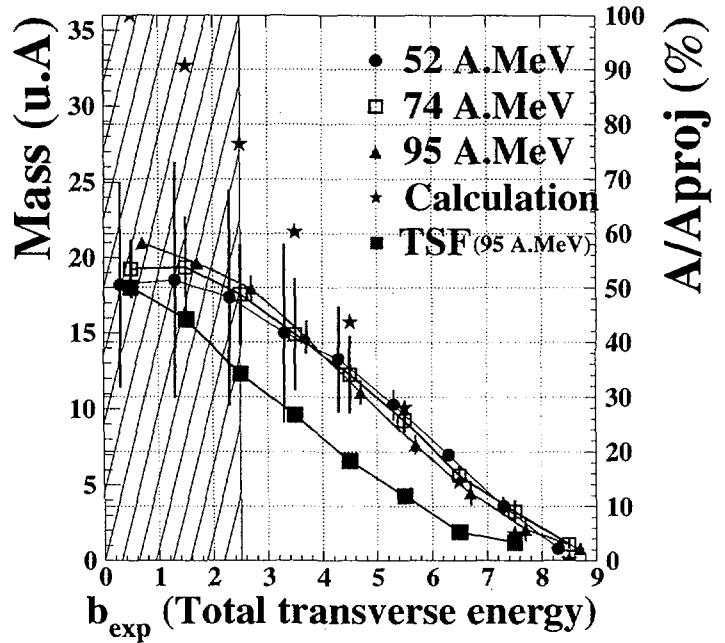


Figure 1

same observations are made on the mean transverse energy and on the slope of the kinetic energy spectra of MRE particles.

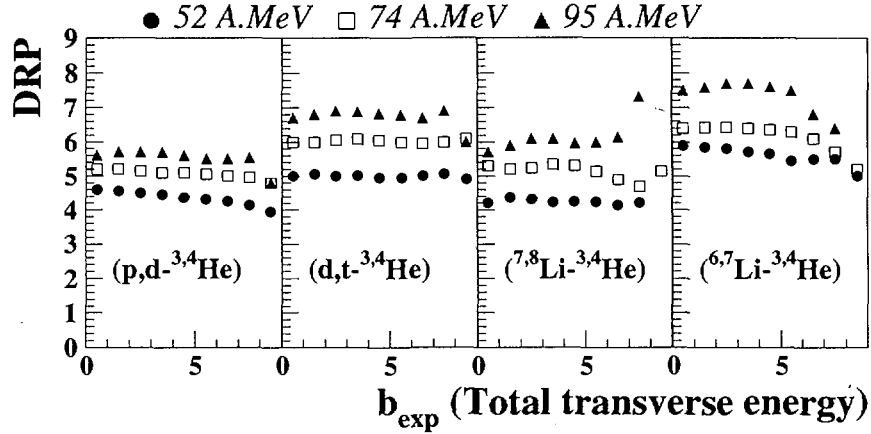


Figure 2

In conclusion, the following trends have been observed in mid-rapidity emissions for Ar+Ni collisions from 52 to 95 A.MeV [3]:

- The amount of particles emitted by MRE is independent of the beam energy, but strongly dependent on the violence (centrality) of the collision. This suggests that this amount is mainly governed by the geometry of the collision.
- The kinematical properties have been found to be strongly dependent on the beam energy but slightly dependent on the violence of the collision. This suggests that the amount of energy exhausted by MRE is only governed by the beam energy.

This strongly suggest a "first-chance collision" process or a "participant-spectator" process. But the rapidity distributions of MRE indicate that several contributions are present, like direct nucleon-nucleon collisions located around $Y_{nn}=0.5 Y_{proj}$, fast emission from the deformed quasi-projectile and quasi-target and/or a neck break-up.

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Comparison between data measured by INDRA and the prediction of the BNV transport model for $^{36}\text{Ar} + ^{58}\text{Ni}$ reaction at 95 A.MeV

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9th September 1998

The study of reaction mechanisms in heavy ion collisions has much advanced recently with the construction of 4π detectors, like INDRA. The formation and the decay of excited nuclei, created in nucleus-nucleus collisions at intermediate bombarding energies ($10 \text{ MeV/u} < E < 100 \text{ MeV/u}$) can be investigated. In this energy regime, it is now well known that the collisions are dominated by binary dissipative processes. In such reactions a quasi-projectile and a quasi-target are formed and their excitation energy increases with decreasing the impact parameter. At variance with the phenomenology of deep inelastic reactions at lower energy ($\approx 10 \text{ MeV/u}$) an intermediate rapidity region between the quasi-projectile and the quasi-target has been observed which is populated by particles and light fragments [1], [2]. The size of this zone increases with energy dissipation, becoming predominant for the most central collisions. Indeed, the nucleons emitted at mid-rapidity should give information about the first steps of the collision. The physical origin of this mid-rapidity emission is most probably a complicated and highly non-equilibrated interplay between one-body and two-body dissipation. If one wants to analyze these events without any a priori hypothesis on the origin of mid-rapidity emission, the reconstruction of sources has to be avoided and all the reaction products have to be studied within a global analysis. The 4π detector INDRA was used to study the $^{36}\text{Ar} + ^{58}\text{Ni}$ reaction at 95 MeV/u . In order to keep a maximum of information, we have chosen to consider only quasi-complete events, in which more than 80% of both total charge ($Z_{\text{tot}} = 46$) and total incident momentum of the system have been measured.

The understanding of such reaction mechanisms in which dynamical effects are predominant, demands careful analysis with a choice of adequate variables and a theoretical modelization through a transport model. BNV [3] is a numerical simulation of the nuclear Boltzmann transport equation. In this approach one calculates the space-time evolution of the one-body distribution function under the influence of the the mean

field, the nucleon-nucleon collisions and the Pauli principle. The nucleon-nucleon elastic cross section entering the collision integral was chosen to be the free one $\sigma_{n-n}(E, \theta, \tau_z)$ where the dependence on energy, scattering angle and isospin is taken from experimental nucleon-nucleon data. With these ingredients, for all impact parameters BNV predicts qualitatively a binary process for the $^{36}\text{Ar} + ^{58}\text{Ni}$ reaction in the sense that even at $b=0$ fm, some memory of the entrance channel is kept. But for intermediate impact parameters an important contribution of matter emitted between the projectile and the target is present. And these nucleons are preferentially produced at mid-rapidity. To compare the data with the BNV prediction we have chosen to avoid all definition of sources and construct one-body observables with data. These observables called global variables condensate the experimental information and allow a more simple characterization of the events by a shape description. One of them the charge density $\rho_z(k)$ [4] is the projection on the main axis of the ellipsoid frame of the charged particles detected in the reaction.

The same technique of analysis can be employed for this model and the data. The results for the charge density $\rho_z(k)$ are represented in figure 1. The relative position between the quasi-projectile peak and the quasi-target peak is well reproduced as well as the population at mid-rapidity. These results indicate that the dissipation is well described in BNV. We have checked that the quality of the agreement is not due to an autocorrelation between the selection variable $H(2)$ and the analysis variable $\rho_z(k)$. In fact, very similar results are obtained if the charge density is analyzed in bins of other global variables uncorrelated to the parallel velocity axis like transverse energy. From this result we can infer that the only important in medium corrections on the nucleon-nucleon cross section is the Pauli blocking on final states [6].

Finally we have observed that the mid-rapidity zone is neutron rich and it could be related to the density dependence of symmetry energy in the equation of state. For a better understanding of this point we plan to replace the interaction which is presently in BNV with a recently proposed Skyrme interaction involving an isospin dependence optimized to exotic nuclei and neutron matter [5].

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Charge Density (Ar+Ni 95 MeV/u)

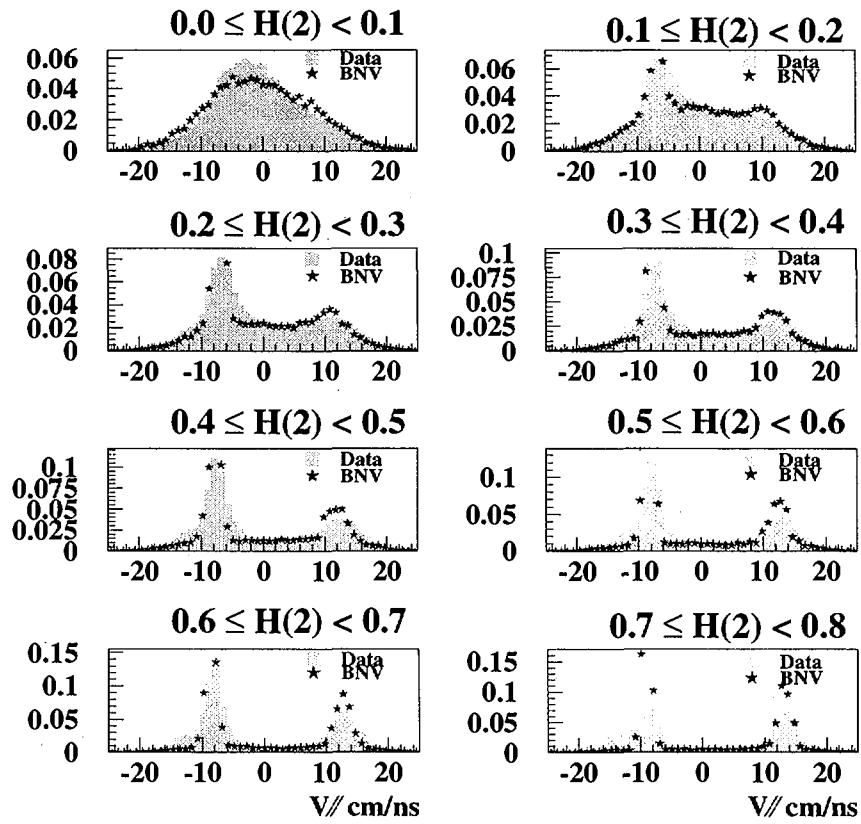


Figure 1: Comparison between data and BNV for charge density and different bins of $H(2)$. The parallel velocity is a normalized axis in the ellipsoid frame.

NON EQUILIBRIUM EMISSION EFFECTS ON QUASI-PROJECTILE PROPERTIES

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INTRODUCTION

It is now well established that binary collisions are the dominant reaction mechanism at intermediate energy. However such collisions are accompanied by non equilibrium emissions observed around mid-rapidity [1]-[2]-[3]-[4].

The quasi-projectile properties of the Ar+Ni reactions at 95A MeV have been studied as a function of the violence of the collision, using a relation between the total transverse energy and the impact parameter. Although the binary character is predominant for all impact parameters [5], an excess of light particles around β_{nn} (nucleon-nucleon velocity) and β_{cm} is observed. It led us to compare a two source analysis, neglecting the mid-rapidity component with a three source analysis which takes into account this emission.

TWO SOURCE ANALYSIS

The sharing of all particles and fragments is made using a method similar to the thrust. In the centre-of-mass frame of the $Z \geq 2$ particles, we calculate respectively the QP (QT) source velocity with particles ($Z \geq 2$) having $v_{//} \geq 1.25v_{CM, Z \geq 2}$ ($v_{//} \leq 0.75v_{CM, Z \geq 2}$). Next we attribute the other charges according to their velocity relative to the QP and QT source velocities. Neutrons are evaluated and added in order to obtain the total mass of the system. Calorimetry method is then used to calculate the excitation energy per nucleon of each source.

THREE SOURCE ANALYSIS

To evaluate the mid-rapidity emission, we suppose that this component is equilibrated and we fit the energy distributions of light particles with three maxwellians (transformed in the laboratory frame) :

$$d^2\sigma/dEd\Omega = \sum_{i=1,3} N_i \sqrt{E_l} \exp - ((E_l + Es_i - 2\sqrt{(E_l Es_i)} \cos(\theta_l))/T_i) \quad (1)$$

N_i , Es_i ($0.5M_{part}V_{source}^2$) and T_i being adjustable parameters and E_l and θ_l , the energy and angle of the particle in the laboratory.

For each light particle and each impact parameter, we fit the sixteen energy distributions (Rings 2 to 17) with the relation (1). The agreement is particularly good at forward angles. For backward angles, over two orders of magnitude, the agreement is still good. We also evaluate the mean multiplicity (above β_{nn}) of each type of particles. Since the fragments present a negligible intermediate velocity contribution, we will use their mean multiplicities evaluated in a two source

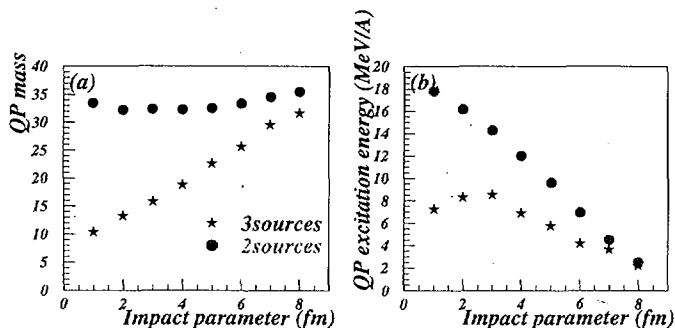


Figure 1: Average QP mass (a) and Excitation energy (b). Two source and three-source analysis lead to quite different results.

analysis in order to calculate the total size of each source.

RESULTS

The quasi-projectile mass is presented in Fig. 1(a). Results are very different for the two types of analysis. We observe a linear increase with the impact parameter for the three source analysis (stars) while the two source analysis (points) leads to a quasi-constant mass around 33. Qualitatively the three source fit results recall those of geometrical model and fireball [6] but they are quantitatively different. The excitation energy of the quasi-projectile is also different according to the method used. The three source method gives, as expected, smaller excitation energy (9 to 2 MeV/A) than the two source analysis (18 to 2 MeV/A). It is then obvious that, if mid-rapidity particles do not origin from a statistical deexcitation process, the quasi-projectile properties have to be studied after removal of intermediate velocity component. The method proposed here (three source fit) gives a rough estimate but cannot be used for a very detailed analysis.

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Evidence for dynamical proton emission in Xe+Sn collisions at 50 MeV/u.

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Experiment : E209/E210.

Particles emitted in intermediate energy (20-200 MeV/u) heavy ion collisions are known to have different origins. In the first stage of the reaction, they are emitted by the interaction zone, during the overlap time of the two colliding nuclei. Then thermal emission by hot nuclei takes place.

In order to get an insight into the presence of non-equilibrium processes in intermediate energy heavy-ion collisions we present in the following a study of proton emission in Xe + Sn data recorded at GANIL by the INDRA multidetector. Selection of the violence of the collision was achieved using the transverse energy E_{t12} carried out by H and He isotopes [1]. We define two class of events: peripheral ($E_{t12} < 240$ MeV) and central ($E_{t12} > 460$ MeV). The mid-rapidity region is then selected between 60° and 120° in the center of mass of the reaction, to avoid thermal emission [1, 2].

We used the relative angle correlation functions between the particles of interest, because they have the property to amplify the effect of low probability processes, and allow to get information on the emission pattern of those particles.

Fig.1 shows the relative angular correlation functions for two protons emitted in the mid-rapidity region as defined above for peripheral (top-left) and central (top-right) collisions. The correlation pattern is rather structureless. To get rid of a possible contamination from both projectile-like and target-like evaporation component at low kinetic energy, we have applied a cut on the proton energy. For $E_p > 20$ MeV and the peripheral collisions, one observes a clear anisotropy of the relative angle correlation: the two protons are preferentially emitted either closely at $\alpha \simeq 0$ or back-to-back.

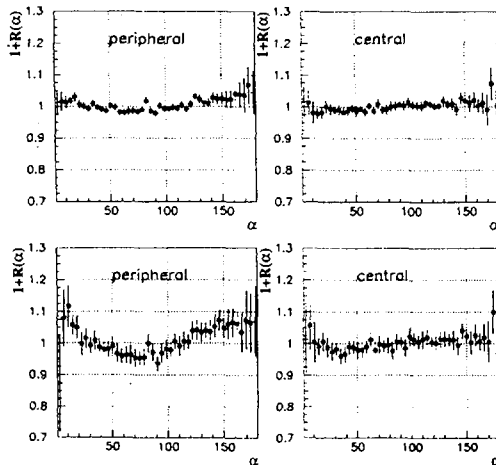


Figure 1: Correlation functions in relative angle between protons emitted in the mid-rapidity region. Top: without any selection of the proton energies, bottom: $E_p > 20$ MeV in the center of mass of the reaction.

We have ruled out possible detector bias and thermal evaporative scenario [4] by using SIMON [3] whose results were filtered by the INDRA acceptance.

Since one cannot explain the observed correlation by the decay of hot sources, we have to foresee a possible out-of-equilibrium origin with the help of a dynamical computation. Indeed, this observed anisotropy might be explained in the light of recent calculations done in the framework of the Landau-Vlasov model [5]. It has been shown in reference [6, 7] that binary dissipative collisions which dominate the reaction cross-section in this incident energy range are accompanied by an abundant dynamical emission (DE) occurring before the separation time, i.e. the birth of the two exit channel nuclei. We made an analog simulation using the Landau-Vlasov equation solved for the momentum dependent Gogny D1-G1 force [8]. for the Xe+Sn system at 50 MeV/A for rather peripheral collisions ($b=8\text{fm}$). In this case, a separation time of about $100\text{fm}/c$ is found. To derive the phase space origin of the dynamical emitted particles, their trajectories are followed backward in time, down to $40\text{fm}/c$ which is the time at which the emission of mid-rapidity particles starts. In fig.2 are displayed equidistant density-profile contours projected on the reaction plane in both the configuration (left) and the momentum space (right). Density profiles are shown for the DE (bottom) and to make the comparison easier, for the whole system (top), i.e. all the particles constituting the two initial nuclei.

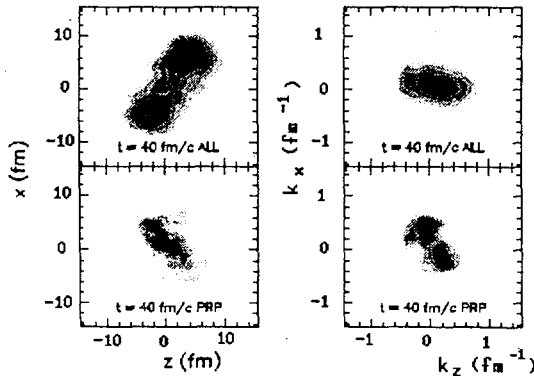


Figure 2: Landau-Vlasov density profiles in space coordinate (left) and momentum coordinate (right) of Xe+Sn at 50 MeV/A and $b=8\text{fm}$. For further details, see the text.

The DE contribution comes mainly from the overlapping zone between the two incoming nuclei and is strongly located at mid-rapidity. Moreover, at such a large impact parameter, two components in the momentum space can be observed in DE as previously seen for the Ar + Al system [7]. This effect is a clear signature of a non-global equilibrium in the participant zone which keeps a strong memory of the entrance channel. This is an evidence when only DE is plotted as in figure 2 (bottom) compared to the whole system (top).

These two components could favour correlations at small and large angles. Another strong argument in favour of this interpretation is that such pattern disappears in central collisions, either in experimental data or in the simulation.

In conclusion, we may argue that a clear evidence for a signal of a dynamical process has been found in peripheral Xe+Sn collisions in the mid-rapidity region. This signal appears clearly when an energy cut is imposed eliminating the thermal contributions. The relative angular correlations then appear to be a very suitable

tool to search for dynamical and primordial processes, together with appropriate dynamical simulations as the Landau-Vlasov ones.

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B3 - MULTIFRAGMENT EMISSION

Expansion Collective Energies and Freeze-out Volume in the multifragmenting Xe + Sn systems from 32 to 50 AMeV Incident Energies

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The multifragmentation of the nuclear system formed in the central collisions of the Xe + Sn reaction between 32 and 50 AMeV has been studied with the INDRA detector¹⁾. We have used the momentum tensor to isolate single sources²⁾ for each incident energy.

From these data the extracted single sources are highly fragmented, the fragments are isotropically emitted and their multiplicities increase slowly from 5.9 to 7.2 with the incident energy. The excitation energies of the sources were reconstructed by employing the calorimetric method. They are rather high and evolve from 7 to 12 AMeV when increasing the incident energy from 32 to 50 AMeV.

A comparison between the experimental data and predictions of the statistical multifragmentation model of Compenhaguen³⁾ (SMM) shows that in order to reproduce the charge distribution and the other static observables lower excitation energies of the single source than the experimental ones are needed⁴⁾. Those calculated excitation energies range from 5 to 7 AMeV (compared to the measured ones : 7-12 AMeV) when the incident energies increase. The good agreement between the experimental and calculated charge partitions validate qualitatively the SMM assumption of thermodynamical equilibrium in the freeze-out volume⁴⁾. However the kinetic observables are more constraining to the model and are difficult to reproduce.

We also used the fragment correlation techniques in order to extract the freeze-out volume and the collective radial energy. With the help of extensive SMM calculations, the freeze-out volume is estimated to be $2.7 V_0$ (V_0 is the normal volume) at 50 AMeV. It decreases with the incident energy to be nearly $2 V_0$ at 32 AMeV. For these freeze-out volumes, the collective energy evolves from 0 to 1.3 AMeV with the bombarding energy. However if we perform the SMM calculation with its standard freeze-out value which is $3 V_0$, the collective radial energy evolves from 0.5 to 2 AMeV. In both cases the expansion is not thermal and originates probably from a dynamical compression developed in the early stage of the reaction. These results are confirmed by the predictions of the expanding emitting source model⁵⁾ (EES).

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Dynamical effects in peripheral and semi-central collisions at intermediate energy.*

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September 11, 1998

The Quantum Molecular Dynamic [1] which describes the time evolution of the nucleon in phase space provides generally a good average description of the dissipative mechanisms occurring all along the interaction between the two colliding nuclei. Some comparisons have been done at different energies for different systems [2] . In our context we will try to get a deeper insight into the reaction mechanisms which could be responsible for the mid-rapidity emission observed in the peripheral and semi-central collision in the reaction Xe+Sn at 50 MeV/nucleon. Simulations have been done for impact parameters between 0 and 12 fm in order to match the total reaction cross section. We have used a soft equation of state ($K=200$ MeV and $\sigma_{nn}=55$ mbarn). The calculation has been stopped at 240 fm/c. At this time the fragments are built by a clusterisation method based on a minimum spanning tree [1] and we have checked that their atomic number is stable. A total number of 60 000 events have been calculated on the whole range of impact parameter. All the events have been filtered by the detector efficiency and the same sorting has been applied to define the shape of the events. We observe for all impact parameters (0 to 12 fm) essentially a binary mechanism; two biggest fragments are located in the velocity space close to the beam and the target velocity respectively. They can be associated with the quasi-projectile and the quasi-target residues. Fig 1 visualises this point, and shows that the velocity and the charge distribution of the biggest fragment ($V_{cm}>0$) are very well reproduced for the mid elongated events.

The small deviation, is essentially due to the clusterisation method used here where the binding energy of the alpha particles is not well reproduced so the biggest fragment has a too large atomic number. However production of IMF and LCP appears in the range of velocities between the velocities of QP and QT. For the same set of events, the multiplicity, the charge distribution and the velocity of the IMF, fig. 2, are fairly reproduced. For the other region, corresponding to less violent collisions the different aspects of the IMF production are also well reproduced.

*O.Tirel and al. in preparation

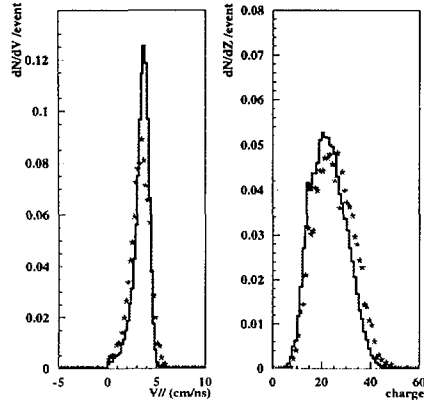


Figure 1: Comparison of velocity and charge distribution of the biggest fragment between experimental data and QMD. The full line and the stars correspond to the data and to QMD calculation, respectively. The comparison has been done for mid-elongated events.

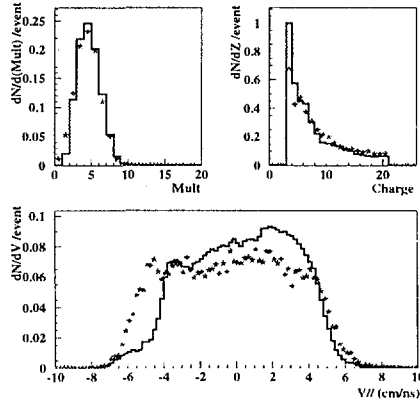


Figure 2: Comparison of the multiplicity, the charge distribution and the velocity of the IMF between experimental data and QMD . The full line and the stars correspond to the data and to the QMD calculation, respectively. The comparison has been done for the mid-elongated events.

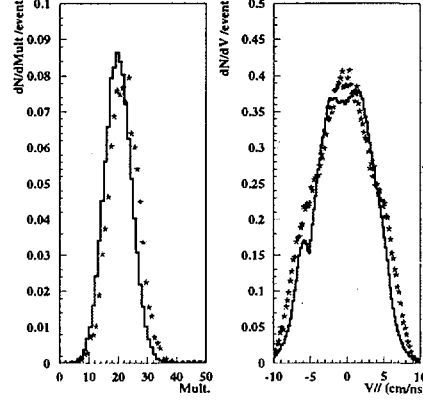


Figure 3: Comparison of the multiplicity and the velocity of the LCP between experimental data and QMD. The full line and the stars correspond to the data and to the QMD calculation, respectively. The comparison has been done for the mid-elongated events.

For LCP, comparison has to be done carefully, essentially for two reasons. QMD model doesn't manage the statistical secondary emission and also the isospin is not well described in this model. In spite of this, the agreement for LCP production (fig 3) is rather good for the two first regions of shape selection. The emission of LCP is preponderant in the mid-rapidity region and can be associated essentially with the first stage of the dynamical process. On the contrary, for the less violent collisions the ratio between dynamical emission and statistical emission is not well reproduced. In these events the proportion of LCP statistically emitted is more important than for the semi-central events. This point reinforces our conclusion concerning the dynamical formation of IMF because although QMD doesn't reproduce well the statistical emission, it reproduces the global characteristics of the fragments. Besides, the fragments in the QMD model are produced in a very fast way, approximately 100-150 fm/c [3] after the contact between the projectile and the target.

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Independence of fragment charge distributions of the size of heavy multifragmenting sources

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A comprehensive interpretation of the decay of highly excited nuclear systems through multifragmentation is not yet achieved. Whether this process finds its origin in the dynamics of nuclear collisions, or results from the statistical decay of hot but thermalized nuclear matter is still largely debated. As a contribution to this question, we report on fragment multiplicities and related Z distributions from single multifragmenting sources with different sizes but with the same available excitation energy per nucleon, resulting from central collisions between heavy nuclei: the 32 MeV/nucleon $^{129}\text{Xe} + ^{\text{nat}}\text{Sn}$ and 36 MeV/nucleon $^{155}\text{Gd} + ^{238}\text{U}$ reactions, with total masses evolving from ~ 248 to $393u$, can lead to composite systems with an excitation energy around 7 MeV/nucleon. The experiment was performed at GANIL, using the 4π multidetector INDRA.¹

For medium and heavy systems in this energy domain the cross section is dominated by binary dissipative processes, accompanied by dynamical or neck emission. To isolate the events resulting from multifragmentation of a single source, a careful selection is thus needed: i) detection of (80%) of the total charge and of the initial “linear momentum” ($Z_p V_p$); ii) selection of compact shape events from among the most dissipative collisions by means of a shape analysis and of the preferred direction of emission of matter, $\theta_{cm} \geq 60^\circ$. Indeed, fragment properties of such events are consistent with the emission from a single source and binary reaction events, if present, are so few as to be negligible.² With such a selection the cross section for “fusion” events is about 1% of the reaction cross section.

The fragment multiplicity distributions for the two systems are shown in fig. 1a: the mean fragment number is 1.5 times larger for the heavier system, which corresponds to the ratio of the total charges of the systems. On the other hand the charge distributions are superimposable, over three orders of magnitude (fig. 1b). Thus the experimental observation is that, around 30 MeV/nucleon, the charge distribution for multifragmentation is independent of the system size, and for a given size, of the entrance channel asymmetry.³ These static properties are also observed for an extended event selection ($30^\circ \leq \theta_{cm} \leq 60^\circ$).⁴ The shape and dynamical characteristics of the events in this zone are however different from those of the single source events.

This type of experimental observation is generally taken as a signature of the dominance of phase space, the emission probability of any fragment being, to first order, only dependent on the temperature of the system. Similar charge and multiplicity distributions, however, also come naturally out of a dynamical model in which multifragmentation is related to the development of volume instabilities, and to the spinodal decomposition of finite nuclei⁵, for which it was shown that the partition in primary fragments of typical charge $Z \sim 10-15$ was favoured. These simulations, in which the evolution of the system is followed during head-on nuclear collisions and up to the cold measurable particles, were performed for each system. The results are shown in fig. 1: a good agreement between

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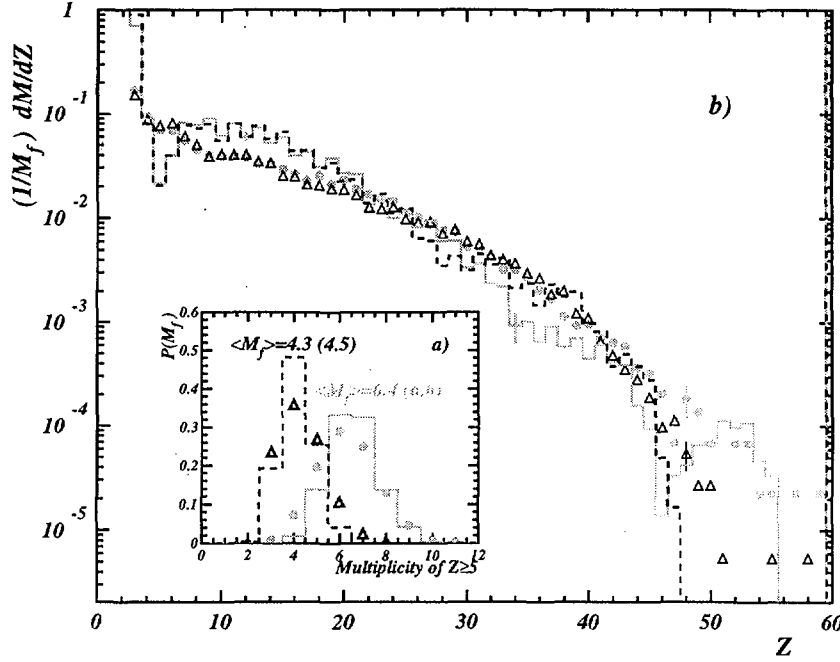


Figure 1: Fragment ($Z \geq 5$) multiplicity (M_f) distributions (a) and differential charge multiplicity distributions, normalised to each event's M_f , (b) for the 32 MeV/nucleon Xe+Sn (triangles; dotted lines) and Gd+U (circles; full lines) systems. Points show the experimental data while the lines are the results of the stochastic mean field simulations. Average experimental (calculated) multiplicity values are given. Some statistical error bars are displayed.

experiment and calculation is observed for the fragment multiplicity and the charge distribution; other variables such as the sizes of the 3 largest fragments are also well reproduced. When decreasing the mass of the system, the experimental conclusions hold for the results of calculations: the charge distribution does not change while the fragment multiplicity decreases. The fragment kinetic energies are however underestimated in the calculation, due to an incomplete account of all possible fluctuations. Works are in progress on this point.

To summarize, we evidenced and characterised the multifragmentation of a single piece of nuclear matter, comprising a large part of two colliding heavy nuclei. When increasing the mass of the system, a scaling law appeared, which consists in increasing the fragment multiplicity proportionally to the charge of the total system while the charge distribution remains unchanged. A possible interpretation is that multifragmentation originates in the spinodal decomposition of nuclei.

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Space Time Characterization of Nuclear Matter in Fragmentation Processes

A.D. Nguyen (LPC Caen) and the INDRA collaboration

Multifragmentation is now a well established process in the Fermi energy range but there is still a large debate concerning the origin of such a phenomenon. A possible way to disentangle among the various processes that have been proposed in the literature is to measure the fragmentation time τ_0 . The present work gives an estimate of τ_0 from a detailed analysis of highly fragmented events in central Xe+Sn collisions at 50 MeV/u studied by the INDRA collaboration [1]. In such collisions, matter is almost stopped and is highly excited resulting in the isotropic emission of several fragments with a collective radial motion of about 2 MeV/u representing a sizeable amount of the total available energy. In order to extract the fragmentation time, the process has been simulated with help of the SIMON event generator [2] to extract the velocity and density profiles at freeze-out. To this end, a number of different initial space-time distribution of the matter have been tested and compared with the data until agreement concerning the mean kinetic energies and velocity distributions of the detected fragments was achieved (black points in the figure). Then, these profiles have been compared with the predictions of a microscopic transport model (BNV) [3] at various instants of the collision (lines in the figure). A reasonable agreement between the experimental distributions and those of the model is obtained for a time between 80 and 100 fm/c after contact time. It turns out that this time corresponds almost exactly to the entrance of the system in the so-called spinodal region in which it becomes mechanically unstable. This suggests that fragmentation could be initiated before the system reaches the unstable region and that the nucleons in each fragments should keep memory of their initial space-time correlations as predicted in QMD calculations [4].

However, recent calculations [5] in which genuine quantum effects have been included seem to shorten the fragmentation time scales and favour spinodal decomposition as the mechanism responsible for nuclear disassembly.

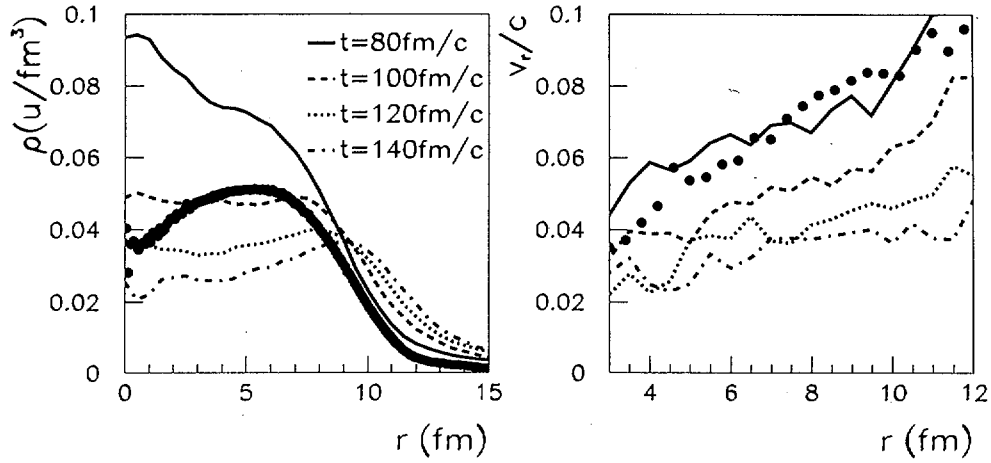


Figure 1: *Comparison between the 'experimental' density and velocity profiles (as deduced from the data by comparison with the Simon results) and those obtained in a microscopic transport model with a soft EoS ($K=200$ MeV).*

'La suite au prochain épisode...'

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Fragment Excitation Energies in Multifragmentation

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Central collisions induced by heavy-ion beams at intermediate energies produce highly excited, compressed nuclear matter. After dynamical compression phase, such systems may expand to a low density where the multifragmentation takes place. The produced primary fragments may be excited and in this case, they are expected to decay by statistical processes. An experimental determination of this secondary component and reconstruction of the excitation energies and sizes of the primary fragments can provide a very significant test of the models and of the assumption of thermodynamical equilibrium at the time of disassembly.

An experimental study^{1,2,3)} of the central collision of the Xe + Sn at 50 AMeV was made using the IMF-LCP correlation techniques. From the IMF-LCP correlation functions we extracted the average multiplicities and kinetic energies of hydrogen and helium isotopes emitted from the primary fragments. Using this information we reconstructed the sizes (charges and masses) and excitation energies of the primary fragments.

The results of these analysis indicate that the fragments are excited, their mean excitation energies per nucleon are all the same, they are equal to 3 AMeV. In addition, we performed maxwellian fit of the kinetic energy spectra of the LCP emitted from the primary fragments. For each particle type, the apparent temperatures fluctuate about a constant value over the whole range of detected fragments ($Z = 4$ to $Z = 20$). These two independent pieces of information provide strong evidence that on the average, thermodynamical equilibrium is achieved when the primary fragments are produced.

Another interesting result is that from a comparison between the predictions of the GEMINI model⁴⁾ with the experimentally observed secondary multiplicities of the evaporated light charged particles, we concluded that the primary fragments have the same N/Z ratio as the initial system $^{129}\text{Xe} + ^{\text{nat}}\text{Sn}$.

We are performing the same analysis for Xe + Sn system but at other incident energies. Preliminary results indicate that the mean excitation energies of the primary fragments are constant for the whole incident energy range, 32 to 50 AMeV.

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Collective motion and angular momentum in 50 A.MeV Xe+Sn central collisions.

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Various features of multifragmentation events for central collisions of Xe+Sn at 50 A.MeV have been recently reported ¹⁾. Besides a high multiplicity and an isotropical emission of the fragments, it has been observed that mean kinetic energies of the fragments could be understood invoking a collective motion superimposed on Coulomb and thermal motion. However, the origin of such a collective motion remained to be clarified. This collective motion may be associated to the thermal pressure of the hot system, or/and to the expansion flow which follows the initial compression built-up in the first stage of the collision. On the other hand, collective rotation induced by angular momenta stored in the multifragmenting source is another possibility which has to be explored.

Angular momentum has been implemented in a statistical model assuming that multifragmentation is dominated by the equipartition of the many-fragments phase space ²⁾. The partitioning is calculated under the constraint of a given size, volume, excitation energy and angular momentum of the source. In the model, it is assumed that the angular momentum is in the orbital motion of the fragments around the center of mass. Respect to a case without angular momentum, the storage of a part of the excitation energy into rotational motion modifies the partition, increasing the yields of the largest fragments and pushing them towards the periphery of the break-up volume.

We have investigated the possible influence of the angular momentum using the Berlin's statistical code of ref. 2 for the multifragmentation events of the central collisions of Xe+Sn at 50 A.MeV. Various calculations have been performed assuming the standard value for the reduced break-up radius (2.2 fm). All the results discussed here have been filtered and selected as the data were. First, we explore the case without angular momentum. For this analysis, the mean size of the biggest fragment together with the total charge bound into fragments have been used to estimate the charge and the excitation energy of the source. Reasonable agreement is observed for the various distributions of the static variables (charge, asymetries of the two or three biggest fragments, fragment multiplicity) with the following parameters respectively for the size, total excitation energy and angular momentum: $Z_s=79$, $E_s=6$ A.MeV, $L_s=0$ (see ref. 3). On the other hand, the mean kinetic energies of the fragments are strongly underestimated. For example, the calculated mean kinetic energy of a fragment of charge $Z=15$ (roughly the charge of the mean biggest fragment) is about twice lower than the experimental value. We have repeated the above procedure for the search of the best parameters, freeing the angular momentum. Static variables are well reproduced with $Z_s=79$, $E_s=8.5$ A.MeV and $L_s=640 \hbar$. A clear improvement is obtained for the kinetic energies of the fragments with charge below 15, but for higher charge, while the experimental values saturate or slightly decrease, the calculated values increase. In the calculation, this behavior is related to the influence of the angular momentum on the location of the biggest fragment which is specific of this kind of modelization but does not seem to be

present in the data. To go further, we have examined the shape of the multifragmentation events in the momentum space. Although variations are seen in the sphericity and coplanarity distributions when one increases angular momentum, the strongest evolution is observed for the aplanarity distribution, since rotational motion tends to induce disk-like shapes. Thus, a high angular momentum, necessary to explain the mean kinetic energy of fragments, fails to reproduce the aplanarity distribution. In fact, as far as the aplanarity distribution is concerned, the agreement with data is better when no rotational motion is assumed. It should be mentioned that this analysis has been performed assuming an unique value for the angular momentum, but it seems difficult to explain simultaneously the aplanarity distribution and mean kinetic energy by imposing a distribution of angular momentum.

To summarize, we have confronted the experimental results of the Xe+Sn central collisions at 50 A.MeV with the predictions of a statistical model which assumes multifragmentation of a rotating hot nuclei. A good agreement is observed for the static variables but the model fails to give a correct picture for the kinematical observables when rotational motion is included. Indeed, the mean kinetic energy of the fragments suggests a high value of angular momentum, and the aplanarity distribution is compatible with no (or a small) angular momentum. Thus, the rotational motion of a thermalized source could not explain the collective motion of the fragments which are produced in the central events of the Xe+Sn reaction at 50 A.MeV.

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MULTIFRAGMENTATION, SCALING LAW AND BINARY DISSIPATIVE COLLISIONS

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Abstract

A scaling law between the fragment multiplicities and the total charge of the $^{129}\text{Xe}+^{nat}\text{Sn}$ and $^{155}\text{Gd}+^{238}\text{U}$ systems has been observed in dissipative binary collisions.

Using the 4π multidetector array INDRA at GANIL, we have investigated the reactions $^{129}\text{Xe}+^{nat}\text{Sn}$ and $^{155}\text{Gd}+^{238}\text{U}$ at, respectively, 32 and 36 A MeV bombarding energies. In a first analysis, a scaling law between the fragment multiplicity and the total charge of the two systems has been observed in a very peculiar class of events: the multifragmentation of single thermalized sources [1]. This selection required, firstly, the detection of "complete events": at least, 80% of the total charge of the system and 80% of the initial "linear momentum" ($Z_p V_p$). Then, an event shape analysis is performed by calculating the eigenvectors of the 3-dimensional kinetic energy tensor of the fragments ($Z \geq 3$) [2]. This analysis allowed to determine the flow angle (Θ_{flow}), i.e. the angle between the beam axis and the eigenvector associated with the largest eigenvalue. The flow angle distribution is strongly forward peaked indicating that these "complete events" keep a strong memory of the entrance channel, as it is expected in binary dissipative collisions. Nevertheless, events populating $\Theta_{flow} \geq 60^\circ$ have been interpreted as events coming from the multifragmentation of a unique source formed in "fusion" reactions [3].

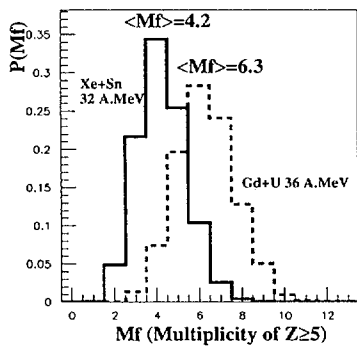


Fig.1: $Z \geq 5$ multiplicities

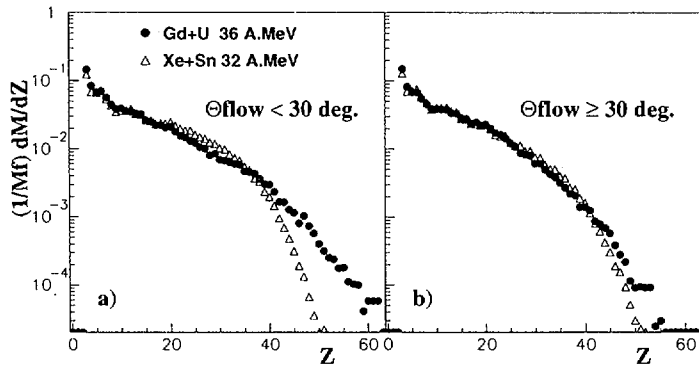


Fig.2: Differential charge multiplicities for $\Theta_{flow} < 30^\circ$ (a) and $\Theta_{flow} \geq 30^\circ$ (b)

In the Fig.1 the $Z \geq 5$ fragment multiplicities are presented for Xe+Sn and Gd+U for the "complete events". We see a perfect scaling law between the

average multiplicities, 4.2 for Xe+Sn and 6.3 for Gd+U, and the total charge of the two systems: 104 and 156, respectively. These values are very close to the ones obtained from the events selected by requiring $\Theta_{flow} \geq 60^\circ$ which correspond to the multifragmentation of single thermalized sources (4.3 for Xe+Sn and 6.4 for Gd+U) [1]. For the single multifragmentating sources, the cross-sections are around 1% of σ_R (total reaction cross-section) for both systems, whereas the "complete event" selections represent, respectively for Xe+Sn and Gd+U, $\sim 10\%$ and $\sim 5\%$ of σ_R .

An interesting point is the comparison of the Z-distribution shapes. In Fig.2, the differential charge multiplicity distributions, normalized to each event's multiplicity (M_f) are superimposed, for Xe+Sn and Gd+U, and displayed for two selections: i) $\Theta_{flow} < 30^\circ$ (Fig.2-a), ii) $\Theta_{flow} \geq 30^\circ$ (Fig.2-b).

For $\Theta_{flow} < 30^\circ$ the Z-distributions are not quite independent of the system sizes (Fig.2-a). Fig.2-b ($\Theta_{flow} \geq 30^\circ$) shows a good superposition of the two Z distributions, exactly as it has been observed in the one-source selection ($\Theta_{flow} \geq 60^\circ$) [1]. Moreover, the shape of the Z-distribution of the Xe+Sn system is independent of the flow angle. It is worthwhile to note that the Xe+Sn system is a quasi-symmetrical system and that the maximum detected Z of the fragments, for any Θ_{flow} , is around 50. This can imply that the Xe+Sn Z-distributions account for the decays of the quasi-projectile (Xe) and the quasi-target (Sn), both excited after binary dissipative collisions. On the other hand, for the Gd+U system, the maximum detected Z is, for $\Theta_{flow} < 30^\circ$, around 60, which is very close to the atomic number of Gd (64). The fission of the uranium target could explain the lack of charge larger than the Gd one.

In conclusion, the scaling law between the IMF multiplicity with the size of the system and the independence of the Z-distributions in $^{129}\text{Xe}+^{119}\text{Sn}$ and $^{155}\text{Gd}+^{238}\text{U}$ are two results which are not specific of the multifragmentation of single thermalized sources. They can be found in more standard dissipative binary collisions. These results suggest that the characteristics of the multifragmentation process are determined in an early time before the degrees of freedom of the system, such as relative energy or (and) event shape, reach full relaxation as this occurs in "fusion" reactions.

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B4 - LIFETIMES OF EXCITED NUCLEI

A straightforward measurement of fission lifetimes by the crystal blocking technique

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The fission lifetime evolution with the initial temperature of an excited nucleus should be a powerful way to get information on the nuclear dissipation processes. Fission lifetimes at high excitation energy have been mainly inferred, up to now, from pre- and post-fission particle multiplicities or GDR- γ multiplicities. However, rather large discrepancies can be found between these experiments, due to strong assumptions in the data analyses. The blocking technique used in the present experiment (E257) is certainly the most straightforward way to measure fission lifetimes but, up to now, this technique could be only used to determine rather long lifetimes, associated with fission at low excitation energies. The availability at GANIL of a very high quality beam of ^{238}U accelerated at 24 MeV per nucleon makes it possible to induce fission events in reverse kinematical reactions, leading to large recoil velocities of the fissioning nuclei. Due to this large velocity, shorter fission times become accessible to the measurement.

The blocking pattern measured for uranium nuclei elastically scattered (figure 1) was used to check during the experiment the crystal properties of the Si target and the quality of the U beam. The fission lifetimes of the uranium-like fragments ($Z=92\pm5$) (PLFs) produced with temperatures up to about 3

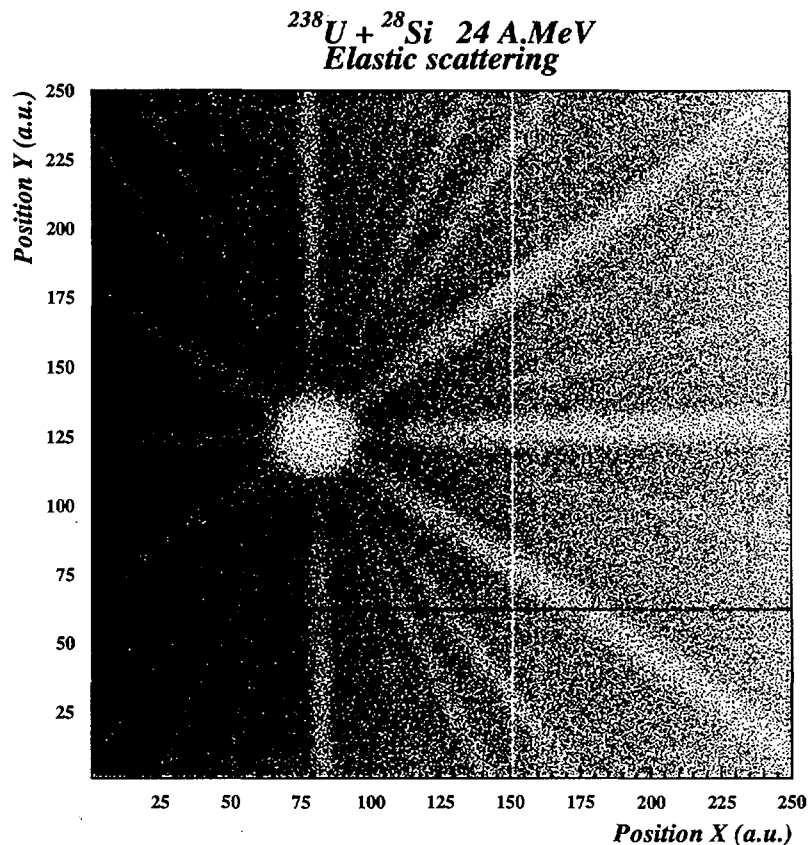


FIGURE 1. Blocking pattern around the $\langle 110 \rangle$ axis for elastically scattered uranium nuclei.

MeV in the $^{238}\text{U} + ^{28}\text{Si}$ reactions at 24 A.MeV have been inferred from a single measurement. The PLF excitation energy was calculated event-by-event from the associated neutron multiplicity measured with ORION, a high efficiency 4π neutron detector. For uranium-like nuclei with temperatures up to about 3 MeV, the fission lifetimes are found much larger than those obtained previously in more indirect approaches.

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F. Goldenbaum et al., Proc. of the XXXVI Int. Winter Meeting on Nucl. Phys., ed I. Iori (Univ. Milano, 1998)

Compound Nuclear Lifetimes at High Excitation Energies via a New Statistical Fluctuation Method

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Compound nuclear lifetimes are connected to statistical properties of nuclei and determine the time scale of statistical de-excitation in heavy ion collisions. Hence, they test the validity of the compound nucleus models at very high excitation energy where it is necessary to compare the various reaction times with the lifetime of a compound nucleus. For example, lifetimes for particle emission at high bombarding energies must be compared to the thermalization process and set the applicability limits for the statistical description of very hot nuclei formed in this type of nuclear reaction. Furthermore, level densities provide a test for nuclear models and their parameters.

A new method to determine compound nuclear lifetimes at high excitation energies was proposed and applied to the system $^{12}\text{C}(^{28}\text{Si}, \alpha)^{36}\text{Ar}$ at two different bombarding energies, 190 and 277 MeV. The first chance alpha particle spectra observed show a structure which directly reflects the fluctuating behavior of the first de-excitation step. Coherence widths and thus lifetimes for the nucleus ^{36}Ar were obtained via a correlation function analysis. The results at low excitation energies are consistent with standard statistical models while the result at high excitation energy is compatible with a theoretically predicted change of the level density parameter (see fig 1). The new experimental method proposed and used to obtain unambiguously the coherence width of compound nuclei at high excitation energies gives a new insight into the physics of high excitation energy nuclear dynamics. The present work has been published in J.M.Casandjian et al, Phys. Lett. B 430 (1998) 43.

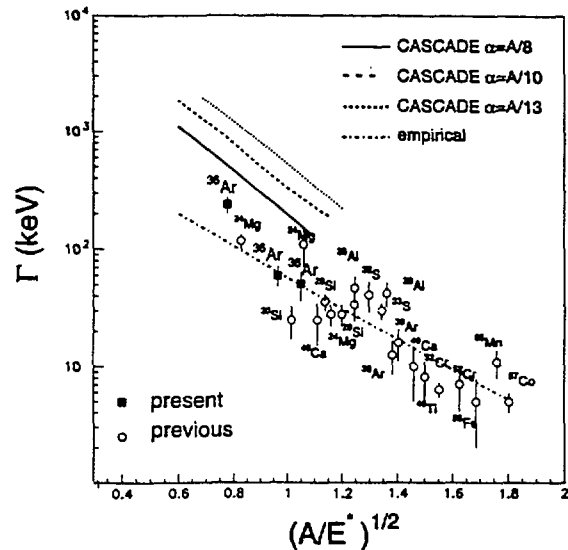


Fig 1: Presently determined widths are compared with the compiled values. The dotted line represents a linear fit to the compiled data. Statistical CASCADE calculations with different density parameters are shown, too.

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C - MISCELLANEOUS

TOURNESOL: a new high efficiency, position sensitive, time-of-flight spectrometer for neutrons.

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When studying the interplay between nuclear structure and reaction mechanism in collisions involving neutron halo nuclei it is very rewarding to measure as many correlated observables as possible for any event. This was well illustrated in another contribution of this progress report (ref.1). When dealing with very weak secondary beams a very high efficiency of all detectors working in coincidence is required. These conditions were met in ref.1 when detecting:

1/ The core (or its components) of the ${}^6\text{He}$ halo nucleus by means of a large area, position sensitive annular telescope.

2/ The thermal energy deposited into the target by means of the high efficiency and 4π neutron multiplicity-meter ORION.

3/ The linear momentum of the halo neutrons as measured with a high efficiency TOF spectrometer.

The latter parameter was then measured with an existing part of the ORION detector, used as a TOF spectrometer. Such a module tested with both mono-energetic neutron beams at Louvain-la-Neuve and later with cosmic rays (ref.2-3) revealed interesting properties of position sensitivity in addition to a very good efficiency. However since this detector had not been designed and thus not optimized for these aims, R&D has been made ending with the design and construction of a new GANIL instrument baptized TOURNESOL.

As explained in ref.3, the position sensitivity of such a detector manifests itself by the differential light yields collected by the phototubes surrounding the detector. Any position of the impact translates into a unique pattern of light yields, thus allowing, after proper calibration and model simulation, the reconstruction of the impact position in both radial distance and azimuthal distance. The position resolution has been observed to depend essentially on the dispersion due to the light distribution during the first collisions when the neutron loses most of its initial energy. Both measured and simulated data lead to a rms of the order of 10 cm indicating that the other sources of dispersion are quite negligible.

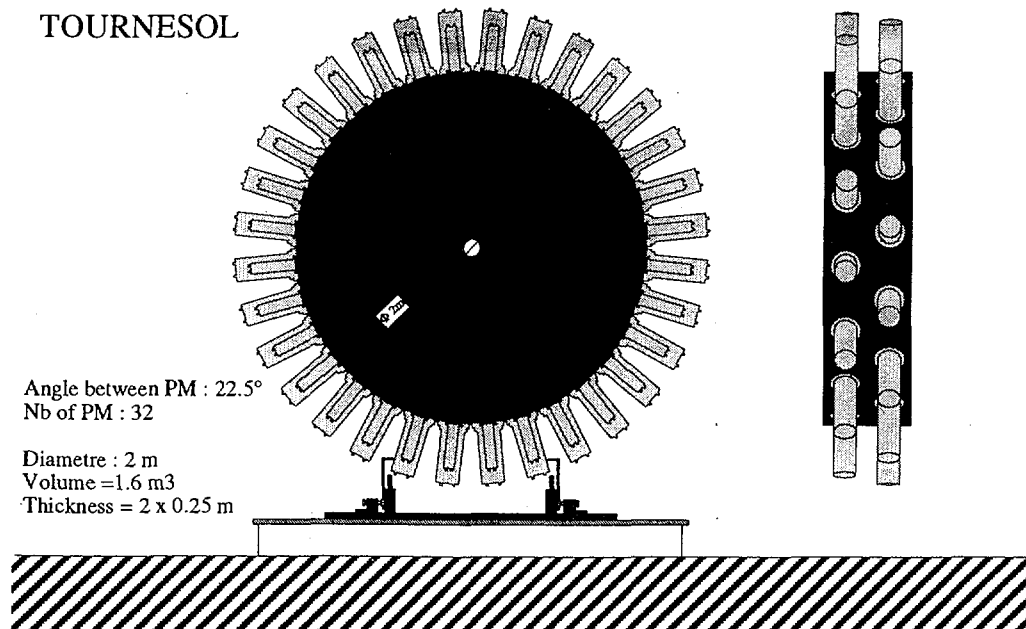


Fig.1 Layout of the TOURNESOL detector

As sketched in Fig.1, the TOURNESOL detector is 2 m in diameter, 50 cm thick, with two optically independent layers 25 cm thick, each. The read out of each cell is made by 16 2" in diameter phototubes, disposed on the detector periphery and viewing the liquid through windows. The scintillator is Gd loaded -as for ORION- enabling the neutron multiplicity measurement as well. TOURNESOL can thus act both as part of the 4π multiplicity-meter and as a position sensitive TOF spectrometer. As was shown in a ref.1, and under proper conditions (very high thresholds on both cells), the double cell enables the handling without ambiguity of the two neutrons emitted from the halo. Test work on the proper location of both neutrons has still to be performed.

In summary, a new TOF and large area spectrometer for neutrons, TOURNESOL, has been built at GANIL. Its combined high efficiency, position sensitivity make of this detector an optimized tool for investigating nuclear reactions involving neutron halo projectiles in a novel way.

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Neutron production in thick Pb targets following spallation reactions

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In the context of several projects (SPIRAL-Phase II, Prospects for a pilot plant for transmutation of nuclear wastes -a so called hybrid reactor coupling a subcritical nuclear reactor with an external neutron spallation source-, ...) it is highly desirable to determine the neutron production following the interaction of light projectiles in thick targets of heavy materials. For this purpose the 4π neutron detector ORION at GANIL is particularly well suited with its high efficiency ($>80\%$) for the few-MeV-neutrons of interest. In contrast with all other techniques used so far in order to measure the average neutron production, this instrument allows for an event by event determination of the production and thus leads to the full neutron multiplicity distribution. This information is of particular value when comparing the measured data with those of model calculations: the shape of the distribution brings strong additional constraints.

With a few thousands incident particles per second only needed for such measurements, of energy up to 200 MeV, the proton secondary beams of GANIL were well suited. They were generated from a primary ^{13}C beam hitting a thick C target and their energies were defined by tuning the magnetic field of the fragment separator. The reaction products were then tagged by means of a thin plastic scintillator located inside the ORION scattering chamber (Fig.1 and ref.1).

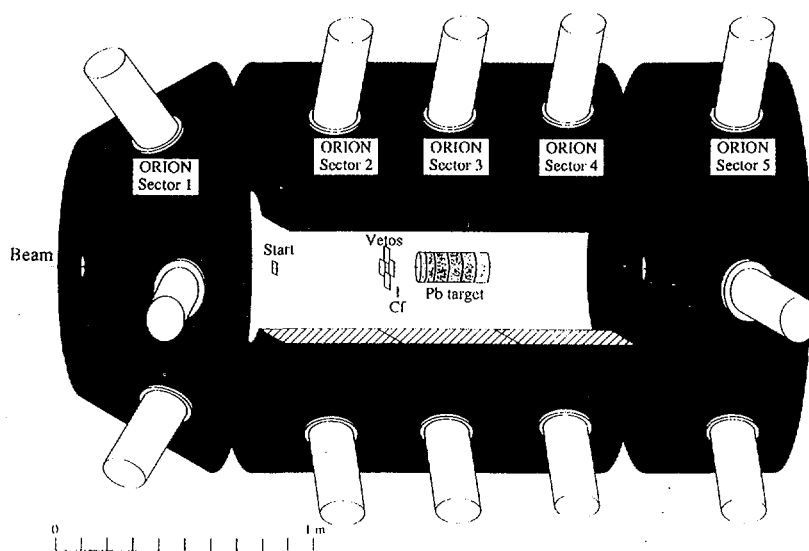


Fig.1 Layout of the experimental setup.

Fig.2 exemplifies the type of multiplicity distributions which were measured for the three scanned projectiles (p, d, α) of similar energy in massive targets. The histograms represent the actual neutron distributions as triggered by the detection of the incident particle whereas the symbols represent the distributions requiring in addition a prompt signal from the neutron detector (for more detail see ref.2). If the two hydrogen isotopes lead to similar neutron distributions, it is shown that α -particles suffer much more the electromagnetic interaction into the target and are thus much less efficient as neutron generators than hydrogen projectiles.

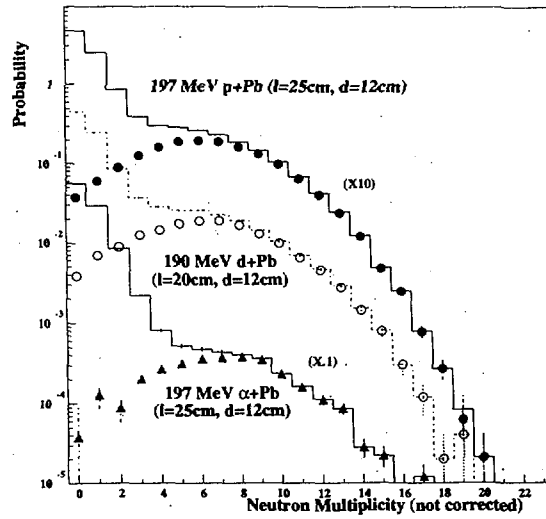


Fig.2 Neutron multiplicity distributions as measured inclusively (histograms) and in coincidence with a prompt signal generated by ORION (symbols) for the p,d and α -particle projectiles.

The influence of the target geometry has been investigated as shown in Fig.3. The difference in neutron production is quite sensitive to the target thickness as long as the latter is less than about twice the considered particle range -sketched by arrows in the figure- and then remains independent of the thickness. It is quite accidental that the neutron production is found to be the same for both isotope projectiles on thick targets at this bombarding energy.

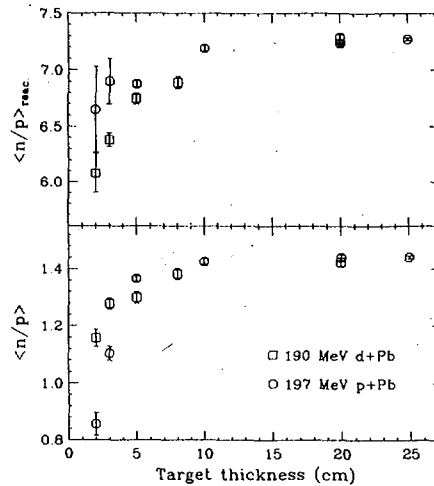


Fig.3. Mean neutron multiplicities (corrected for background and detector efficiency) of the inclusive distributions (lower panel) and those associated with reaction events as defined in the text (upper panel)

Similar measurements have been conducted in a more extensive way at higher energies (Ref.3) at CERN and recently at COSY-Jülich (Ref.4) in order to get an overview of spallation neutron production in a very broad energy range on various materials with varying geometries. It is the first set of data ever recorded, using all the same and very powerful 4π measurement approach.

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- 4 NESSI Collaboration (in progress)

COSMIC RAY INSTRUMENT CALIBRATION (E-285)

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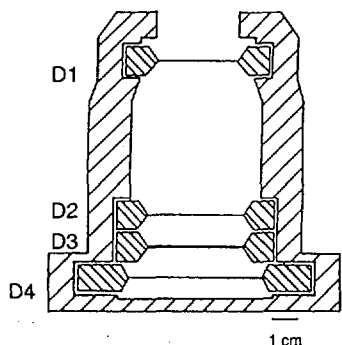
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Abstract.— A low-energy cosmic ion detector instrument (called PESCA, Solar Energetic Particles and Anomalous galactic cosmic rays Component) composed of a telescope, its amplification electronic and data processing unit has been designed and will be constructed. The instrument is able to detect ions from hydrogen to iron at energy range of 1– 50 MeV/ nucleon. The electronics have been designed using space components, so its weight, dimensions and power consumption would be small enough to allow the system to be used for cosmic ion detection in space onboard Russian PHOTON satellite. In order to study its actual performances, the instrument need to be calibrated at an heavy ion accelerator.

1. Instrument description.— The instrument consists of three main parts: telescope, analog electronics (AE) and digital electronics (DE).

1.1. Telescope.— The telescope is made up of four silicon ion implanted detectors placed in a cylindrical aluminum frame (Fig. 1). Table 1 gives the characteristics of these cylindrical detectors. Detector thickness were selected by calculating how far the ions to be detected could penetrate silicon. The first two detectors, D₁ and D₂, are basically tracking detectors, but D₂ also stops very low energy particles. D₃ is a stopping detector and D₄ is a veto detector for particles which are not stopped at the third detector. The D₁ detector should be thin enough to register the minimum detectable energy range with a cut off at about 2 MeV/nucleon for He and 4 MeV/nucleon for Fe. The D₃ detector must be able to stop the 50 MeV/nucleon Fe ions that hit it after crossing the D₁ and D₂ detectors. Last, the D₄ detector has the most active area, so that it will more efficiently detect ions escaping D₃, for similar reason the D₃ detector has a less active area. Detectors positions were calculated (Fig. 1) in order to have an acceptance angle of approximately 50° which is wide enough for particles escaping D₃ detector to be caught by D₄ detector and not to escape through the aluminum structure. Additionally, at this acceptance angle, the incident particles should not have a range greater than 15% that of the vertical ones.



	D1	D2	D3	D4
Area (cm ²)	3	4,5	4,5	9
Thickness (μm)	31	150	1014	100
Resistivity (kΩ cm)	0,408	1,8	12,5	1,9
Dead layer (μg/cm ²)	40,0 Au 40,1 Al	40,0 Au 40,0 Al	40,1 Au 40,0 Al	40,0 Au 40,0 Al

Fig. 1: Schematic representation of detector telescope.

1.2. Analog electronics (AE).— AE consists of five stages. The first stage (Amplification) amplifies the detector pulses. It is composed by four preamplifiers (Amptek A250) and four amplifiers (Amptek A275) with negative feedback to avoid instabilities caused by

active component non-linearities and temperature effects. Detector instabilities in the baseline make the use of a baseline restorer necessary; an Amptek BLR1 integrated circuit was used for this purpose. The peak detector is composed by a PD 06 of WMT-Electronic. The coincidence/anti-coincidence stage is adjusted so that the output signal is only emitted if the D_1 and D_2 coincide while D_4 is in anti-coincidence; therefore the discrimination logic used is $D_1 D_2 \bar{D}_4$. Amptek A150 pulse amplitude discriminators with two output gates have been used. This circuit triggers the conversion stage. The control circuit coordinates the conversion of analogue pulse to digital value. Three electronic chains, each composed of a Harris sample and hold HA5330 model and a Maxim analog-to-digital converter (ADC) MAX162 model make up the conversion stage.

1.3. Digital electronics (DE).— DE consists of two interfaces one with satellite another with AE and one data processing unit using one MAS281 micro-processor.

2. Calibration.— In the calibration we intent to obtain the instrument performance in charge and mass discriminations for ions of energies below 50 MeV/uma. In April 1997 the calibration was performed under the following characteristics:

Beam: ^{58}Ni , 52 MeV/uma

Targets: ^{12}C of 18,5 mg/cm² and ^{197}Au of 57,9 mg/cm²

Telescope position: 45 cm from target at angles from 2° to 90° with respect to incident beam.

Experimental room: Nautilus.

The Fig. 2 shows two of results obtained.

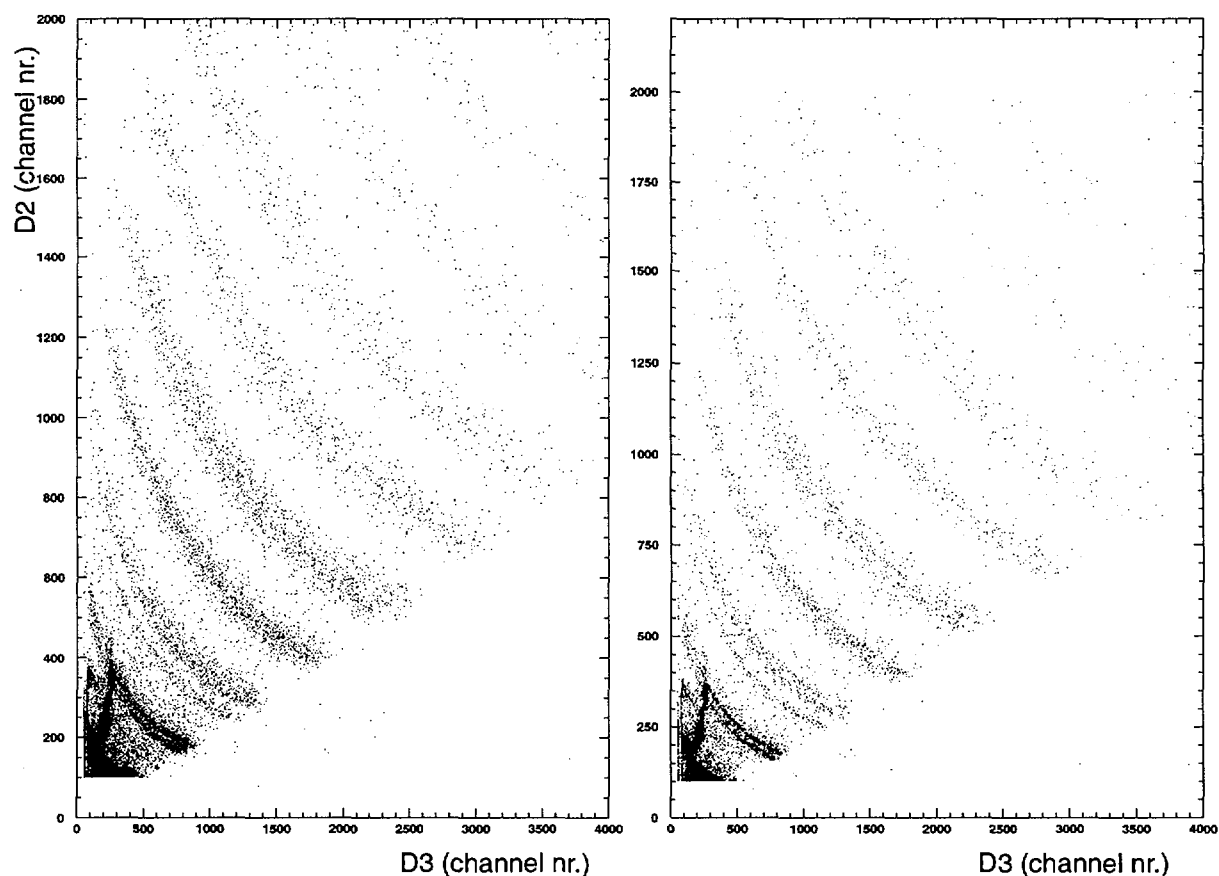


Fig. 2.— Calibration results obtained with ^{197}Au target at 5° and 7° respectively.

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ANGULAR DISTRIBUTION OF PROTONS EMITTED FROM ORIENTED NUCLEI: TOWARDS IMAGING SINGLE-PARTICLE WAVE FUNCTIONS

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A major drawback of most quantum mechanical measurements is that they produce only quantities averaged over coordinates or time; nuclear physics is no exception. There is, however, an observable (the angular distribution with respect to the deformation axis of single nucleons emitted from metastable states in oriented nuclei) that is directly related to the spatial distribution of the single-particle wave function, as will be shown in this report. It will also be argued that measuring the probability densities of nucleons in nuclei (not only matrix elements) is more promising and that it should become a new trend in evaluating our understanding of nuclear structure in the future.

Density maps from angular distributions

To calculate the angular distribution with respect to the nuclear symmetry axis of a proton emitted from a metastable state in a deformed nucleus, we have solved numerically the time-dependent Schrödinger equation in two dimensions [1, 2]

$$i\hbar \frac{\partial}{\partial t} \psi(z, \rho, t) = \mathcal{H}(z, \rho) \psi(z, \rho, t) \quad (1)$$

where the hamiltonian \mathcal{H} is

$$\mathcal{H}(z, \rho) = -\frac{\hbar^2}{2\mu} \left[\frac{1}{\rho} \frac{\partial}{\partial \rho} + \frac{\partial^2}{\partial \rho^2} + \frac{\partial^2}{\partial z^2} - \frac{\Lambda^2}{\rho^2} \right] + V(z, \rho) \quad (2)$$

Initial single-proton excited states in ²⁰⁸Pb, as those represented in Fig. 1, were chosen in the frame of a deformed Woods-Saxon potential, characterized by the deformation parameter ϵ ($\simeq \beta_2$ for small ϵ).

Knowing $\psi(z, \rho, t)$, one can estimate the tunneling probability as a function of azimuthal angle θ :

$$P_{tun}(t, \theta) = \int_{r_B(\theta)}^{\infty} |\psi(r, \theta, t)|^2 r^2 dr \quad (3)$$

where $r_B(\theta)$ is the radial position of the potential ridge in the direction θ . The results are shown in Fig. 2 for the '2h' quasi-stationary states at $\epsilon = 0.1$ from Fig. 1.

Except for $\Lambda = 0$, none of these wave functions escapes along the path of minimum barrier ($\theta = 0^\circ$). The main directions of emission are determined by the angles between the branches of the initial wave function and the z axis. The anisotropic barrier acts like a filter modifying the relative intensities of different branches but does not change their directions. Consequently, the emission does not always occur along the nuclear symmetry axis as was intuitively predicted in

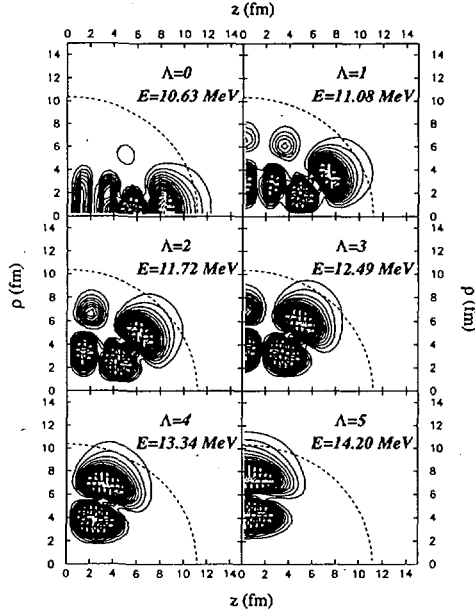


Figure 1: $|\psi_{2h}(z, \rho)|^2$ at $\epsilon = 0.1$.

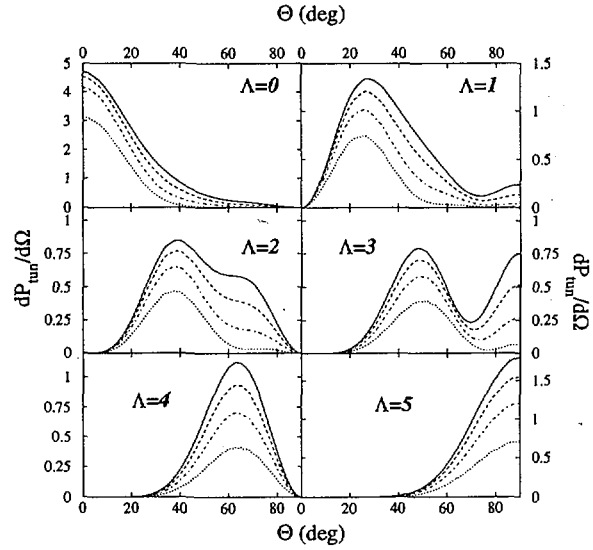


Figure 2: Angular distributions of the '2h' states at $\epsilon = 0.1$.

Ref. [3]. It is therefore possible in most cases to deduce the number of branches in the proton density and their orientations just by inspecting the angular distribution. For more complete information it is, however, necessary to simulate the filter, *i.e.*, to calculate the tunneling through a bidimensional barrier. A detailed study of the connection between angular distributions and density maps is in progress.

In conclusion, quite accurate maps of single-particle density distributions in deformed nuclei can be obtained by combining a) angular distribution measurements of single nucleons emitted from metastable states in oriented nuclei, and b) numerical simulations of quantum tunneling through an anisotropic coulomb + centrifugal barrier. This would represent the first direct measurement of probability densities of nucleons in nuclei and would allow one to test nuclear models on a deeper and more detailed level.

After this work was completed we found that pronounced anisotropies – such as those calculated above – have been recently observed during a similar process involving α emission from oriented nuclei [4]. Although α decay is easier to measure, proton or neutron decay represents a better tool for exploring in detail the wave functions involved since: a) the modification of the initial wave anisotropy by the tunneling filter is less important, and b) one samples a single particle wave function at a time and not an overlap of the four nucleons entering into the formation amplitude of an α particle, and c) it carries higher angular momenta.

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MODEL-UNRESTRICTED NUCLEUS-NUCLEUS SCATTERING POTENTIALS FROM MEASUREMENT AND ANALYSIS OF $^{16}\text{O} + ^{16}\text{O}$ SCATTERING

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SEARCH FOR THE SIGNATURE OF A HALO STRUCTURE IN THE $p(^6\text{He}, ^6\text{Li})n$ REACTION

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GIANT DIPOLE RESONANCE IN VERY HOT NUCLEI OF MASS $A = 115$

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GIANT DIPOLE EMISSION AS A PROBE OF THE ENTRANCE CHANNEL DYNAMICS

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LIMITING TEMPERATURES FOR COLLECTIVE MOTION : THE GIANT DIPOLE RESONANCE IN VERY HOT NUCLEI

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INFN LNS - CATANIA, IPN - ORSAY, DAPNIA CEA SACLAY - GIF SUR YVETTE, GANIL - CAEN, NBI - COPENHAGEN

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ARE GIANT RESONANCES HARMONIC VIBRATIONS?

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REGULARITY AND CHAOS IN VLASOV EVOLUTION OF NUCLEAR MATTER

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ELASTIC SCATTERING OF ^6He AND ITS ANALYSIS WITHIN A FOUR-BODY EIKONAL MODEL

AL-KHALILI J.S. ET AL.

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IDENTIFICATION OF HYDROGEN ISOTOPES WITH THE BaF₂ ELECTROMAGNETIC CALORIMETER TAPS

MATULEWICZ T. ET AL.

GANIL - CAEN, LPC - CAEN

NIM A378 (1996) 179.

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FLUID DYNAMICAL APPROACH TO SPINODAL INSTABILITIES IN FINITE NUCLEAR SYSTEMS

JACQUOT B. ET AL.

GANIL - CAEN, TTU - COOKEVILLE, LNS - CATANIA

PHYSICS LETTERS B383 (1996) 247.

96 63 A

PRE-EQUILIBRIUM EFFECTS IN THE POPULATION OF GIANT DIPOLE RESONANCES

FLIBOTTE S. ET AL.

DPA McMASTER UNIV. - HAMILTON, AECL - CHALK RIVER, GANIL - CAEN, DP UNIV. OF TORONTO - TORONTO

PHYSICAL REVIEW LETTERS 77, 8 (1996) 1448.

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FIRST SPECTROSCOPIC STUDY OF ²²Si

BLANK B ET AL.

CENBG - GRADIGNAN, GSI - DARMSTADT, INST. FÜR KERNPHYSIK TH DARMSTADT, LPC ISMRA - CAEN

PHYSICAL REVIEW C54, 2 (1996) 572.

96 65 A

SPECTROSCOPY OF LIGHT- AND MEDIUM-MASS PROTON-RICH NUCLEI

BLANK B.

CENBG - GRADIGNAN

EXTREMES OF NUCLEAR STRUCTURE

PROCEEDINGS OF THE INTERNATIONAL WORKSHOP XXIV ON GROSS PROPERTIES OF NUCLEI AND NUCLEAR EXCITATIONS

HIRSCHEGG (AT) 1996

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ELASTIC SCATTERING AND CHARGE EXCHANGE REACTIONS WITH EXOTIC BEAMS

CORTINA-GIL M.D.

GANIL - CAEN, DAPNIA CE SACLAY - GIF SUR YVETTE, FRL Mc GILL UNIV. - MONTREAL, IPN - ORDAY,

SCNP UNIV. OF SURREY - GUILDFORD, IFUSP DFN - SAO PAULO, LPC ISMRA - CAEN

EXTREMES OF NUCLEAR STRUCTURE

PROCEEDINGS OF THE INTERNATIONAL WORKSHOP XXIV ON GROSS PROPERTIES OF NUCLEI AND NUCLEAR EXCITATIONS

HIRSCHEGG (AT) 1996

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THE MANY FACETS OF GIANT RESONANCES AT HIGH EXCITATION ENERGIES

BARAN V. ET AL.

IFA - BUCAREST, GANIL - CAEN, LNS INFN - CATANIA, INR - KIEV, ILLINOIS UNIV. - URBANA

PROCEEDINGS OF THE GRONINGEN CONFERENCE ON GIANT RESONANCES

GRONINGEN (NL) 1995

NUCLEAR PHYSICS A599, 1,2 (1996) 29c.

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EFFECTIVE GAMMA DEFORMATION NEAR $A = 130$ IN THE INTERACTING BOSON MODEL

VOGEL O. ET AL.

INST. FÜR KERNPHYSIK - KOLN, GANIL - CAEN

PHYSICAL REVIEW C53, 4 (1996) 1660.

96 89 A

SUPERSYMMETRIC MULTIPHONON STRUCTURE

KIM K.H. ET AL.

TOKYO UNIV. - TOKYO, INST. FÜR KERNPHYSIK - KOLN, GANIL - CAEN

PHYSICAL REVIEW LETTERS 76, 19 (1996) 3514.

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UNEXPECTED PROPERTIES OF THE SCISSORS MODE IN THE ODD-MASS NUCLEUS ^{167}Er

SCHLEGEL C. ET AL.

INST. FÜR KERNPHYSIK - DARMSTADT, GANIL - CAEN

PHYSICS LETTERS B375 (1996) 21.

96 91 A

PARTICLE-HOLE EXCITATIONS IN THE INTERACTING BOSON MODEL (I) GENERAL STRUCTURE AND SYMMETRIES

DE COSTER C. ET AL.

ITP VAKGROEP SUBAT.STRALINGSFYSICA - GENT, GANIL - CAEN, IP FRIBOURG UNIV. - FRIBOURG, SCHOOL OF PHYSICS - ATLANTA

NUCLEAR PHYSICS A600 (1996) 251.

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SELECTED ASPECTS OF COLLECTIVE MOTIONS IN NUCLEI : ORDER AND DISORDER

CHOMAZ PH.

GANIL - CAEN

ANNALES DE PHYSIQUE 21 (1996) 669.

96 93 A

RECENT RESULTS ON ELASTIC AND INELASTIC SCATTERING

ALAMANOS N. ET AL.

CE SACLAY - GIF-SUR-YVETTE, GANIL - CAEN

ANNALES DE PHYSIQUE 21 (1996) 601.

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STUDY OF THE UNBOUND NUCLEUS ^{11}N BY ELASTIC RESONANCE SCATTERING

AXELSSON L. ET AL.

CHALMERS TEKNISKA HOGSKOLA - GÖTEBORG, INST. DE ESTRUCTURA DE LA MATERIA - MADRID,

KURCHATOV INST. - MOSCOW, IPN - ORSAY, ABO ACADEMI - TURKU, GANIL - CAEN, AARHUS UNIV. -

AARHUS, LPC - CLERMONT FERRAND, JINR - DUBNA

PHYSICAL REVIEW C54, 4 (1996) R1511.

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NEW ISOMER $^{32}\text{Al}^m$

ROBINSON M. ET AL.

GANIL - CAEN, IAP - BUCHAREST, JINR - DUBNA, LPC ISMRA - CAEN

PHYSICAL REVIEW C53 (1996) 1465.

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MASS MEASUREMENT OF ^{100}Sn

CHARTIER M. ET AL.

GANIL - CAEN, IFUSP - SAO PAULO, DNP AUSTRALIAN NAT. UNIV., CEN SACLAY - GIF SUR YVETTE,

BERGEN UNIV. FYSIK INST. - BERGEN, LPC ISMRA - CAEN, DIP. DI FIS. CATANIA UNIV. - CATANIA

PHYSICAL REVIEW LETTERS 77, 12 (1996) 2400.
96 67 C

FIRST OBSERVATION OF THE $T_z = -7/2$ NUCLEI ^{45}Fe AND ^{49}Ni

BLANK B. ET AL.

CENBG - GRADIGNAN, GSI - DARMSTADT, IEP WARSAW UNIV. - WARSAW, GANIL - CAEN

PHYSICAL REVIEW LETTERS 77, 14 (1996) 2893.

96 70 C

MASS MEASUREMENT OF ^{100}Sn AND ^{100}In USING THE SECOND CYCLOTRON OF GANIL AS A HIGH RESOLUTION MASS SPECTROMETER

MITTIG W. ET AL.

GANIL - CAEN, IFUSP - SAO PAULO, DNP AUSTRALIAN NAT. UNIV., CEN SACLAY - GIF SUR YVETTE, UNIV. BERGEN - BERGEN, LPC ISMRA - CAEN, IPN - ORSAY, UNIV. CATANIA - CATANIA

EXTREMES OF NUCLEAR STRUCTURE

PROCEEDINGS OF THE INTERNATIONAL WORKSHOP XXIV ON GROSS PROPERTIES OF NUCLEI AND NUCLEAR EXCITATIONS

HIRSCHEGG (AT) 1996

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ASTROPHYSICS WITH NEUTRON-RICH NUCLEI

SORLIN O.

IPN - ORSAY

EXTREMES OF NUCLEAR STRUCTURE

PROCEEDINGS OF THE INTERNATIONAL WORKSHOP XXIV ON GROSS PROPERTIES OF NUCLEI AND NUCLEAR EXCITATIONS

HIRSCHEGG (AT) 1996

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SPECTROSCOPY OF LIGHT EXOTIC NUCLEI

OSTROWSKI A.N. ET AL.

GANIL - CAEN, HMI - BERLIN, OHIO UNIV. - ATHENS, JINR - DUBNA, RRCKI - MOSCOW

EXTREMES OF NUCLEAR STRUCTURE

PROCEEDINGS OF THE INTERNATIONAL WORKSHOP XXIV ON GROSS PROPERTIES OF NUCLEI AND NUCLEAR EXCITATIONS

HIRSCHEGG (AT) 1996

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NEUTRON-RICH ISOTOPES $^{54-57}\text{Ti}$

DORFLER T. ET AL.

GOTTINGEN UNIV. - GOTTINGEN, MAINZ UNIV. - MAINZ, IPN - ORSAY, GANIL - CAEN

PHYSICAL REVIEW C54, 6 (1996) 2894.

96 86 C

RELATIVISTIC MEAN-FIELD STUDY OF LIGHT PROTON-RICH NUCLEI ^{18}Ne , ^{20}Mg AND ^{22}Si

REN Z. ET AL.,

GANIL - CAEN, NANJING UNIVERSITY - NANJING, FJG INSTITUT FÜR KERNPHYSIK - JÜLICH

ZEITSCHRIFT FÜR PHYSIKS A353 (1996) 363-365

96 96 C

LIGHT PARTICLE-EVAPORATION RESIDUE COINCIDENCES FOR THE $^{79}\text{Br} + ^{27}\text{Al}$ SYSTEM AT 11.8 MeV/NUCLEON

GOMEZ DEL CAMPO J. ET AL.

ORNL - OAK RIDGE, GANIL - CAEN, UNIV. NACIONAL AUTONOMA DE MEXICO - MEXICO, DAPNIA CE SACLAY - GIF-SUR-YVETTE

PHYSICAL REVIEW C53, 1 (1996) 222.

96 04 D4

DISAPPEARANCE OF FLOW AND THE IN-MEDIUM NUCLEON-NUCLEON CROSS SECTION FOR $^{64}\text{Zn} + ^{27}\text{Al}$ COLLISIONS AT INTERMEDIATE ENERGIES

ZHI YONG HE ET AL.

LPC ISMRA - CAEN, IMP - LANZHOU, GANIL - CAEN, IPN - LOUVAIN-LA-NEUVE, SUBATECH - NANTES, TEXAS A&M UNIV. - COLLEGE STATION, INST.NUCL.RES. - SHANGHAI, VAPOLI UNIV. - NAPLES

NUCLEAR PHYSICS A598 (1996) 248.

96 05 D

DYNAMICAL ANALYSIS OF DISSIPATIVE COLLISIONS BETWEEN Ar AND Ag NUCLEI IN THE FERMI ENERGY DOMAIN

HADDAD F. ET AL.

SUBATECH - NANTES, TEXAS A&M UNIV. - COLLEGE STATION, IPN - ORSAY

ZEITSCHRIFT FÜR PHYSIKS A354 (1996) 321.

96 10 D

ORBITING FEATURES IN THE STRONGLY DAMPED BINARY DECAY OF THE $^{28}\text{Si} + ^{16}\text{O}$ SYSTEM

OLIVEIRA J.M. ET AL.

IFUSP DFN - SAO PAULO, DCM UNIV. DE SOROCABA, GANIL - CAEN, LABOR. TANDAR - BUENOS AIRES

PHYSICAL REVIEW C53, 6 (1996) 2926.

96 38 D

EVIDENCE FOR COULOMB FISSION OF ^{238}U IN THE INTERACTION OF 24.3 MeV/NUCLEON ^{23}U WITH ^{197}Au : A NEW EXPERIMENTAL APPROACH

PIASECKI E. ET AL.

IEP WARSAW UNIV. - WARSAW, HEAVY ION LAB. WARSAW UNIV. - WARSAW, WARSAW UNIV. OF AGRICULTURE - WARSAW, SINS - SWIERK, GANIL - CAEN, IF UNIV. SAO PAULO - SAO PAULO, IPN - ORSAY, HMI - BERLIN

PHYSICS LETTERS B377 (1996) 235.

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PRODUCTION OF RADIONUCLIDES BY 1.7 GeV PROTON-INDUCED REACTIONS ON CdTe CRYSTALS

PORRAS E. ET AL.

DEPT. MAT. APLICADA Y ASTRONOMIA - BURJASSOT, PHYS. DEPT. UNIV. OF SOUTHAMPTON, CIEMAT - MADRID, IFC - BURJASSOT, DEPT. DE FIS. UPN - PAMPLONA, GANIL - CAEN

NIM B111 (1996) 315.

96 46 D

ONSET OF COLLECTIVE EXPANSION IN NUCLEUS-NUCLEUS COLLISIONS BELOW 100 MeV/u

JEONG S.C. ET AL.

LPC ISMRA - CAEN, DP SOONGSIL UNIV. - SEOUL, GANIL - CAEN, DAPNIA CE SACLAY - GIF SUR YVETTE, IPN UCL - LOUVAIN-LA-NEUVE, LPN - NANTES, IMP - LANZHOU, DSF INFN - NAPOLI

NUCLEAR PHYSICS A604 (1996) 218.

96 50 D

HEATING OF NUCLEI WITH ENERGETIC ANTIPROTONS

GOLDENBAUM F. ET AL.

HMI - BERLIN, CERN - GENEVE, TU-MUNCHEN - GARCHING, GANIL - CAEN, INR RUSSIAN ACAD.SCI. - MOSCOW, WARSAW UNIV. - WARSZAWA, FZ-ROSSENDORF - DRESDEN, IPN - ORSAY

PHYSICAL REVIEW LETTERS 77, 7 (1996) 1230.

96 56 D

NEUTRON FROM THE BREAKUP OF ^{19}C

MARQUES F.M. ET AL.

LPC ISMRA - CAEN, FI CTH - GÖTEBORG, DP SURREY UNIV. - GUILDFORD, SPSR BIRMINGHAM UNIV.,
CRN - STRASBOURG, IPN - ORSAY, ULB - BRUXELLES, NSCL MSU-EAST LANSING, GANIL-CAEN, IP
UCL-LOUVAIN LA NEUVE, IFA AARHUS UNIV.-AARHUS, DL - WARRINGTON

PHYSICS LETTERS B381 (1996) 407.

96 61 D

ONE-NUCLEON TRANSFER REACTIONS TO CONTINUUM STATES INDUCED BY HEAVY ION PROJECTILES

LHENRY I. ET AL.

IPN - ORSAY, GANIL - CAEN, DAPNIA CE SACLAY - GIF SUR YVETTE, NSCL MSU - EAST LANSING, DP
CENTRAL MICHIGAN UNIV. - Mt. PLEASANT, UNIV. FEDERAL - RIO DE JANEIRO

PHYSICAL REVIEW C54, 2 (1996) 593.

96 66 D

DECAY PATTERNS OF TARGET-LIKE AND PROJECTILE-LIKE NUCLEI PRODUCED IN $^{84}\text{Kr} + ^{197}\text{Au}$, ^{nat}U REACTIONS AT $E/A = 150$ MeV

QUEDNAU B.M. ET AL.

GANIL - CAEN, HMI - BERLIN, IFUSP DFN - SAO PAULO, IPN - ORSAY, KVI - GRONINGEN, LN SATURNE -
GIF SUR YVETTE

NUCLEAR PHYSICS A606 (1996) 538.

96 68 D

STUDY OF SHORT-LIVED ISOMERS PRODUCED IN THE FRAGMENTATION-LIKE REACTIONS

LEWITOWICZ M.

GANIL - CAEN

EXTREMES OF NUCLEAR STRUCTURE

PROCEEDINGS OF THE INTERNATIONAL WORKSHOP XXIV ON GROSS PROPERTIES OF NUCLEI AND
NUCLEAR EXCITATIONS

HIRSCHEGG (AT) 1996

96 75 D

REACTION MECHANISM IN HIGHLY FRAGMENTED Pb + Au COLLISIONS AT 29 MeV/u

LECOLLEY J.F. ET AL.

LPC ISMRA - CAEN, CRN - STRASBOURG

PHYSICS LETTERS B387 (1996) 460.

96 80 D

^9B PROTON HALO VIA REACTION AND BREAKUP CROSS SECTION MEASUREMENTS

NEGOITA F. ET AL.

IAP - BUCHAREST-MAGURELE, GANIL - CAEN, IPN - ORSAY, FLNR JINR - DUBNA, NPI - REZ, IEP
WARSAW UNIV. - WARSAW

PHYSICAL REVIEW C54, 4 (1996) 1787.

96 81 D

KINEMATICAL PROPERTIES AND COMPOSITION OF VAPORIZING SOURCES : IS THERMODYNAMICAL EQUILIBRIUM ACHIEVED ?

BORDERIE B. ET AL.

IPN - ORSAY, LPC ISMRA - CAEN, GANIL - CAEN, IPNL - VILLEURBANNE, DAPNIA CEN SACLAY - GIF
SUR YVETTE, SUBATECH - NANTES

PHYSICS LETTERS B388 (1996) 224.

96 82 D

VAPORIZATION EVENTS FROM BINARY DISSIPATIVE COLLISIONS

RIVET M.F. ET AL.

IPN - ORSAY, GANIL - CAEN, SUBATECH - NANTES, IPNL - VILLEURBANNE, LPC ISMRA - CAEN,
DAPNIA CEN SACLAY - GIF SUR YVETTE

PHYSICS LETTERS B388 (1996) 219.

96 83 D

**COMMENT ON "ANALYSIS OF HARD TWO-PHOTON CORRELATIONS MEASURED IN
HEAVY-ION REACTIONS AT INTERMEDIATE ENERGIES"**

MARQUES F.M. ET AL.

GANIL - CAEN, LPC - CAEN, WARSAW UNIV. - WARSZAWA, KVI - GRONINGEN

PHYSICAL REVIEW C54, 5 (1996) 2783.

96 84 D

**PION REABSORPTION IN HEAVY-ION COLLISIONS INTERPRETED IN TERMS OF THE
DELTA CAPTURE PROCESS**

HOLZMANN R. ET AL.

GANIL - CAEN, GSI - DARMSTADT, KVI - GRONINGEN, IFC - BURJASSOT, GIESSEN UNIV. - GIESSEN, NPI
- PRAHY, CENBG - GRADIGNAN

PHYSICS LETTERS B366 (1996) 63.

96 02 F

**SUBTHRESHOLD PION DYNAMICS AS A SOURCE FOR HARD PHOTONS BEYOND
PROTON-NEUTRON BREMSSTRAHLUNG IN HEAVY-ION COLLISIONS**

GUDIMA K.K. ET AL.

GANIL - CAEN, GSI - DARMSTADT, KVI - GRONINGEN, IFC - BURJASSOT

PHYSICAL REVIEW LETTERS 76 (1996) 2412.

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**IMPORTANCE OF ONE- AND TWO-BODY DISSIPATION AT INTERMEDIATE ENERGIES
STUDIED BY HARD PHOTONS**

VAN POL J.H.G. ET AL.

KVI - GRONINGEN, GANIL - CAEN, GSI - DARMSTADT, GIESSEN UNIV. - GIESSEN, IFC - BURJASSOT,
SLOVAK ACAD.SCI. - BRATISLAVA, NPI - PRAHY

PHYSICAL REVIEW LETTERS 76 (1996) 1425.

96 08 F

**NUCLEAR STOPPING IN HEAVY-ION COLLISIONS AT 100 MeV/NUCLEON FROM
INCLUSIVE AND EXCLUSIVE NEUTRAL PION MEASUREMENTS**

BADALA A. ET AL.

INFN - CATANIA, CATANIA UNIV. - CATANIA, INFN LNS - CATANIA

PHYSICAL REVIEW C53 (1996) 1782.

96 12 F

**THE ROLE OF NUCLEAR INCOMPRESSIBILITY IN THE PRODUCTION OF HARD
PHOTONS IN HEAVY-ION COLLISIONS**

SCHUTZ Y.,

GANIL - CAEN

PROCEEDINGS OF THE GRONINGEN CONFERENCE ON GIANT RESONANCES

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NUCLEAR PHYSICS A599, 1,2 (1996) 97c.

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STUDY OF MULTIFRAGMENTATION PATTERNS INDUCED BY SPINODAL INSTABILITIES

COLONNA M. ET AL.

GANIL - CAEN, LNS - CATANIA

NUCLEAR PHYSICS A613 (1997) 165.

97 03 A

THE SCISSORS MODE IN THE PRESENCE OF A NEUTRON SKIN

WARNER D.D. ET AL.

CCLRC DARESBURY LAB. - DARESBURY, GANIL - CAEN

PHYSICS LETTERS B395 (1997) 145.

97 21 A

THE SPECTROSCOPY OF ^{22}Al : A β p, β 2p AND $\beta\alpha$ EMITTER

BLANK B. ET AL.

CENBG - GRADIGNAN, LPC ISMRA - CAEN, GSI - DARMSTADT, INST.FUR KERNPHYSIK - DARMSTADT

NUCLEAR PHYSICS A615 (1997) 52.

97 22 A

SHELL MODEL STUDY OF THE NEUTRON-RICH NUCLEI AROUND $N = 28$

RETAMOSA J. ET AL.

CRN - STRASBOURG, GANIL - CAEN, UNIV. AUTONOMA DE MADRID - MADRID

PHYSICAL REVIEW C55, 3 (1997) 1266.

97 23 A

TRANSFER RESULTS FOR ODD-ODD ^{199}Au AS A TEST OF EXTENDED SUPERSYMMETRY

BERRIER-RONSIN G. ET AL.

IPN - ORSAY, GANIL - CAEN, IP UNIV. DE FRIBOURG - FRIBOURG

PHYSICAL REVIEW C55, 3 (1997) 1200.

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NUCLEAR ASTROPHYSICS WITH RADIOACTIVE BEAMS

VERVIER J.

IPN - LOUVAIN-LA-NEUVE

EUROPHYSICS NEWS 28 (1997) 25.

97 25 A

FRAGMENT MOMENTUM DISTRIBUTIONS AND THE HALO

ORR N.A.

LPC ISMRA - CAEN

PROCEEDINGS OF THE FOURTH INTERNATIONAL CONFERENCE ON RADIOACTIVE NUCLEAR BEAMS

OMIYA (JP) 1996

NUCLEAR PHYSICS A616 (1997) 155c.

97 28 A

STUDY OF WEAKLY BOUND AND UNBOUND STATES OF EXOTIC NUCLEI WITH BINARY REACTIONS

BOHLEN H.G. ET AL.

HMI - BERLIN, FLNR JINR - DUBNA, GANIL - CAEN, DPA OHIO UNIV. - ATHENS

PROCEEDINGS OF THE FOURTH INTERNATIONAL CONFERENCE ON RADIOACTIVE NUCLEAR BEAMS

OMIYA (JP) 1996

NUCLEAR PHYSICS A616 (1997) 254c.

97 32 A

MASS MEASUREMENTS NEAR $N = Z$

MITTIG W. ET AL.

GANIL-CAEN, LPC- CAEN, CSNSM-ORSAY, INFN-CATANIA, IPN - ORSAY, IFUSP-SAO PAULO, JINR-DUBNA, NSCL MSU-EAST LANSING, LANL-LOS ALAMOS, RSPHySE-CANBERRA, CE SACLAY-GIF-SUR-YVETTE, UNIV. DI CATANIA- CATANIA, UNIV. I BERGEN - BERGEN

PROCEEDINGS OF THE FOURTH INTERNATIONAL CONFERENCE ON RADIOACTIVE NUCLEAR BEAMS

OMIYA (JP) 1996

NUCLEAR PHYSICS A616 (1997) 329c.

97 34 A

T = 0 VERSUS T = 1 PAIRING IN THE INTERACTING BOSON MODEL

VAN ISACKER P. ET AL.

GANIL - CAEN, CCLRC DARESBUURY LAB. - DARESBUURY

PHYSICAL REVIEW LETTERS 78, No.17 (1997) 3266.

97 35 A

IONIC CHARGE DEPENDENCE OF THE INTERNAL CONVERSION COEFFICIENT AND NUCLEAR LIFETIME OF THE FIRST EXCITED STATE IN ^{125}Te

ATTALLAH F. ET AL.

CENBG - GRADIGNAN, STANFORD UNIV. - STANFORD, CIRIL - CAEN, CSNSM - ORSAY, GANIL - CAEN

PHYSICAL REVIEW C55, 4 (1997) 1665.

97 37 A

BETA-p, 2p,-ALPHA SPECTROSCOPY OF $^{22,23,24}\text{Si}$ AND ^{22}Al

CZAJKOWSKI S. ET AL.

CENBG - GRADIGNAN, INST.FUR KERNPHYSIK - DARMSTADT, LPC ISMRA - CAEN, GSI - DARMSTADT

NUCLEAR PHYSICS A616 (1997) 278c.

PROCEEDINGS OF THE FOURTH INTERNATIONAL CONFERENCE ON RADIOACTIVE NUCLEAR BEAMS

OMIYA (JP) 1996

97 39 A

RPA INSTABILITIES IN FINITE NUCLEI AT LOW DENSITY

JACQUOT B. ET AL.

GANIL - CAEN, CE SACLAY - GIF-SUR-YVETTE, LNS - CATANIA, TENNESSEE TECH.UNIV. -

COOKEVILLE, MIDDLE EAST TECH.UNIV. - ANKARA

NUCLEAR PHYSICS A617 (1997) 356.

97 41 A

PROTON ELASTIC SCATTERING ON LIGHT NEUTRON-RICH NUCLEI

CORTINA-GIL M.D. ET AL.

GANIL - CAEN, CE SACLAY - GIF-SUR-YVETTE, FOSTER RAD.LAB. MCGILL UNIV. - MONTREAL, LLNL - LIVERMORE, IPN - ORSAY, IFUSP DFN - SAO PAULO, LPC ISMRA - CAEN

PHYSICS LETTERS B401 (1997) 9.

97 42 A

A CYCLOTRON AS A POWERFUL TOOL FOR MASS MEASUREMENTS OF EXOTIC NUCLEI

CHARTIER M. ET AL.

GANIL - CAEN, IFUSP - SAO PAULO, AUSTRALIAN NAT. UNIV. - CANBERRA, CEN SACLAY - GIF-SUR-YVETTE, BERGEN UNIV. - BERGEN, LPC ISMRA - CAEN, CATANIA UNIV. - CATANIA

INTERNATIONAL CONFERENCE ON ELECTROMAGNETIC ISOTOPE SEPARATORS AND TECHNIQUES RELATED TO THEIR APPLICATIONS

PROCEEDINGS OF THE 13th INTERNATIONAL CONFERENCE ON ELECTROMAGNETIC ISOTOPE SEPARATORS AND TECHNIQUES RELATED TO THEIR APPLICATIONS

BAD DURKHEIM (DE) 1996

NIM B126, 1-4 (1997) 334.

97 45 A

PHASE TRANSITION IN NUCLEAR MATTER ?

AUGER G. ET AL.

GANIL - CAEN, IPN - ORSAY, LPC ISMRA - CAEN, IPN LYON - VILLEURBANNE, CEN SACLAY - GIF-SUR-YVETTE, SUBATECH - NANTES

CRITICAL PHENOMENA AND COLLECTIVE OBSERVABLES

PROCEEDINGS OF CRIS '96 - 1st CATANIA RELATIVISTIC ION STUDIES

ACICASTELLO (IT) 1996

97 50 A

REACTION MECHANISMS IN MEDIUM ENERGY COLLISIONS : INFLUENCE OF DYNAMICAL FLUCTUATIONS

COLONNA M. ET AL.

LNS INFN - CATANIA, GANIL - CAEN

CRITICAL PHENOMENA AND COLLECTIVE OBSERVABLES

PROCEEDINGS OF CRIS '96 - 1st CATANIA RELATIVISTIC ION STUDIES

ACICASTELLO (IT) 1996

97 51 A

INSTABILITIES IN FINITE SYSTEMS

BELKACEM M. ET AL.

INFN LNS - CATANIA, GANIL - CAEN, INFN SEZIONE DI CATANIA - CATANIA

CRITICAL PHENOMENA AND COLLECTIVE OBSERVABLES

PROCEEDINGS OF CRIS 96 - 1st CATANIA RELATIVISTIC ION STUDIES

ACICASTELLO (IT) 1996

97 52 A

THE $^{12}\text{C} + ^{24}\text{Mg}$ ELASTIC SCATTERING : AN EXAMPLE OF ANOMALOUS TRANSPARENCY AT COULOMB BARRIER ENERGIES

SCIANI W. ET AL.

IFUSP - SAO PAULO, SYNCHROTRON RAD. RES. INST. - HYOGO, DEPT. CIENCIAS EXATAS -

SOROCABA, GANIL - CAEN

NUCLEAR PHYSICS A620 (1007) 91.

97 56 A

SPECTROSCOPIC STUDIES OF THE βp AND β2p DECAY OF ^{23}Si

BLANK B. ET AL.

CENBG - GRADIGNAN, INST. FÜR KERNPHYSIK - DARMSTADT, LPC ISMRA - CAEN, GSI - DARMSTADT

ZEITSCHRIFT FÜR PHYSIK A357 (1997) 247.

97 69 A

A NUCLEAR MASS FORMULA BASED ON SU(4) SYMMETRY

VAN ISACKER P. ET AL.

GANIL - CAEN, FYSISK INST. BERGEN UNIV. - BERGEN

FOUNDATIONS OF PHYSICS 27, 7 (1997) 1047.

97 73 A

HEATING NUCLEI WITH HIGH-ENERGY ANTIPROTONS

LOTT B. ET AL.

GANIL - CAEN, HMI - BERLIN, CERN - GENEVE, TU MUNICHEN - GARCHING, INR RUSSIAN ACAD. OF SCI.

- MOSCOW, WARSAW UNIV. - WARZAWA, FZ ROSSENDORF - DRESDEN, IPN - ORSAY

NUCLEAR PHYSICS SUPPL. 56A (1997) 114.

97 83 A

^{40}Ti BETA DECAY AND THE NEUTRINO CAPTURE CROSS SECTION OF ^{40}Ar

TRINDER W. ET AL.

GANIL - CAEN, IPN - ORSAY, NOTRE DAME UNIV. - NOTRE DAME, WASHINGTON UNIV. - SEATTLE
PHYSICS LETTERS B415 (1997) 211.

97 99 A

ANALYTICALLY SOLVABLE MEAN-FIELD POTENTIAL FOR STABLE AND EXOTIC NUCLEI

STOITSOV M.V. ET AL.

INST. OF NUCL. RES. & NUCL. ENERGY - SOFIA, BARTOL RES. INST. - NEWARK, GANIL - CAEN, INST.
DE CIENCIAS NUCLEARES - MEXICO, INST. DE FIS. LAB. DE CUERMACARA - MEXICO

PHYSICS LETTERS B415 (1997) 1.

97 100 A

SPECTROSCOPY OF ^{11}N

OSTROWSKI A.N. ET AL.

DEPT. PHYS. & ASTR. EDINBURGH UNIV. - EDINBURGH, UNIVERSIDADE DE SAO PAULO - SAO
PAULO, HMI - BERLIN, INST. ATOMIC PHYS. - BUCAREST, GANIL - CAEN, DSM CE SACLAY - GIF SUR
YVETTE, LPC - CAEN

INTERNATIONAL WINTER MEETING ON NUCLEAR PHYSICS

PROCEEDINGS OF THE XXXV INTERNATIONAL WINTER MEETING ON NUCLEAR PHYSICS

BORMIO (IT) 1997

RICERCA SCIENTIFICA ED EDUCAZIONE PERMANENTE SUPPL.110, p.127.

97 102 A

COULOMB MULTIPHONON EXCITATION IN HEAVY ION COLLISIONS

LANZA E.G. ET AL.

CATANIA UNIV. AND INFN - CATANIA, DEPART. DE FIS. ATOM. MOL. NUCL. SEVILLA UNIV. - SEVILLA,
GANIL - CAEN, IPN - ORSAY

INTERNATIONAL WINTER MEETING ON NUCLEAR PHYSICS

PROCEEDINGS OF THE XXXV INTERNATIONAL WINTER MEETING ON NUCLEAR PHYSICS

BORMIO (IT) 1997

RICERCA SCIENTIFICA ED EDUCAZIONE PERMANENTE SUPPL.110, p.148.

97 104 A

COULOMB EXCITATION EXPERIMENTS AT GANIL

SORLIN O. ET AL.

IPN - ORSAY, LPC - CAEN, IAP - BUCHAREST, CSNSM - ORSAY, GANIL - CAEN, CE SACLAY - GIF SUR
YVETTE, FLNR JINR - DUBNA, GSI - DARMSTADT

INTERNATIONAL WINTER MEETING ON NUCLEAR PHYSICS

PROCEEDINGS OF THE XXXV INTERNATIONAL WINTER MEETING ON NUCLEAR PHYSICS

BORMIO (IT) 1997

RICERCA SCIENTIFICA ED EDUCAZIONE PERMANENTE SUPPL.110, p.566.

97 108 A

THERMODYNAMICAL EQUILIBRIUM UP TO THE GAS PHASE ?

GULMINELLI F. ET AL.

IPN - ORSAY, LPC - CAEN, GANIL - CAEN, IPNL - VILLEURBANNE, CEN SACLAY - GIF SUR YVETTE,
SUBATECH - NANTES

INTERNATIONAL WINTER MEETING ON NUCLEAR PHYSICS

PROCEEDINGS OF THE XXXV INTERNATIONAL WINTER MEETING ON NUCLEAR PHYSICS

BORMIO (IT) 1997

RICERCA SCIENTIFICA ED EDUCAZIONE PERMANENTE SUPPL.110, p.396.

97 111 A

PROTON EMISSION IN INELASTIC SCATTERING OF ^{40}Ca ON ^{40}Ca AT 50 MeV/NUCLEON

SCARPACI J.A. ET AL.

IPN - ORSAY, GANIL - CAEN, DSM CE SACLAY - GIF SUR YVETTE, KVI - GRONINGEN

PHYSICAL REVIEW C56 (1997) 3187.

97 113 A

ELASTIC AND QUASIELASTIC SCATTERING OF ^3He FROM ^{12}C

TOSTEVIN J.A. ET AL.

SURREY UNIV. - GUILDFORD, NOTRE DAME UNIV. - NOTRE DAME, NSCL MSU - EAST LANSING, GANIL - CAEN, ANL - ARGONNE

PHYSICAL REVIEW C56 (1997) R2929.

97 114 A

EVIDENCE FOR A HIGHLY DEFORMED OBLATE O^+ STATE IN $^{74}_{36}\text{Kr}$

CHANDLER C. ET AL.

SURREY UNIV. - GUILDFORD, CENBG - GRADIGNAN, BRIGHTON UNIV. - BRIGHTON, WARSAW UNIV. - WARSAW, GANIL - CAEN, LPC ISMRA - CAEN, OLIVER LODGE LAB. - LIVERPOOL, IP & NE - BUCAREST, YORK UNIV. - YORK, DARESBUY LAB. - WARRINGTON

PHYSICAL REVIEW C56 (1997) R2924.

97 115 A

NUCLEAR SPIN ALIGNMENT AND STATIC MOMENTS OF LIGHT PROJECTILE FRAGMENTS MEASURED WITH THE LEVEL MIXING RESONANCE (LMR) METHOD

NEYENS G. ET AL.

INST. VOOR KERN- EN STRALINGSFYSICA - LEUVEN, GANIL - CAEN, CE SACLAY - GIF SUR YVETTE, INST. PHYS. UNIV. SAO PAULO - SAO PAULO

PHYSICS LETTERS B393 (1997) 36.

97 07 B

DYNAMICAL EFFECTS AND INTERMEDIATE MASS FRAGMENT PRODUCTION IN PERIPHERAL AND SEMICENTRAL COLLISIONS OF $\text{Xe}+\text{Sn}$ AT 50 MeV/NUCLEON

LUKASIK J. ET AL.,

IPN - ORSAY, GANIL - CAEN, LPC ISMRA - CAEN, IPNL - VILLEURBANNE, CE SACLAY - GIF-SUR-YVETTE, SUBATECH - NANTES

PHYSICAL REVIEW C55, 4 (1997) 1906.

97 36 B

MULTIFRAGMENTATION WITH BROWNIAN ONE-BODY DYNAMICS

GUARNERA A. ET AL.

GANIL - CAEN, LNS - CATANIA, CE SACLAY - GIF-SUR-YVETTE, NSD LBNL - BERKELEY

PHYSICS LETTERS B403 (1997) 191.

97 54 B

EXPERIMENTS WITH ISOMERIC BEAMS

PFUTZNER M. ET AL.

INST. EXP. PHYS. WARSAW UNIV. - WARSAW, GSI - DARMSTADT, GANIL - CAEN, CERN - GENEVA
INTERNATIONAL CONFERENCE ON NUCLEAR PHYSICS AT STORAGE RINGS

PROCEEDINGS OF THE THIRD INTERNATIONAL CONFERENCE ON NUCLEAR PHYSICS AT STORAGE RINGS

BERNKASTEL-KUES (DE) 1996

NUCLEAR PHYSICS A626 (1997) 259c.

97 101 B

A POSSIBLE SCENARIO FOR THE TIME DEPENDENCE OF THE MULTIFRAGMENTATION PROCESS IN $\text{Xe} + \text{Sn}$ COLLISIONS (AN EXPLANATION OF THE 3He PUZZLE)

BOUGAULT R. ET AL.

LPC - CAEN, GANIL - CAEN, IPN - ORSAY, CEN SACLAY - GIF SUR YVETTE, SUBATECH - NANTES, IPNL - VILLEURBANNE

INTERNATIONAL WINTER MEETING ON NUCLEAR PHYSICS

PROCEEDINGS OF THE XXXV INTERNATIONAL WINTER MEETING ON NUCLEAR PHYSICS
BORMIO (IT) 1997
RICERCA SCIENTIFICA ED EDUCAZIONE PERMANENTE SUPPL.110, p.251.
97 103 B

MULTIFRAGMENTATION OF HEAVY SYSTEMS : CHARACTERISTICS AND SCALING LAWS

RIVET M.F. ET AL.
IPN - ORSAY, GANIL - CAEN, LPC - CAEN, IPNL - VILLEURBANNE, CEN SACLAY - GIF SUR YVETTE,
SUBATECH - NANTES, IPNE IFA - BUCHAREST, LPN - QUEBEC
INTERNATIONAL WINTER MEETING ON NUCLEAR PHYSICS
PROCEEDINGS OF THE XXXV INTERNATIONAL WINTER MEETING ON NUCLEAR PHYSICS
BORMIO (IT) 1997
RICERCA SCIENTIFICA ED EDUCAZIONE PERMANENTE SUPPL.110, p.225.
97 105 B

SEARCH FOR DYNAMICAL EFFECTS IN THE MULTIFRAGMENTATION PROCESS AT INTERMEDIATE ENERGY

GERMAIN M. ET AL.
SUBATECH - NANTES, LPC - CAEN, GANIL - CAEN
INTERNATIONAL WINTER MEETING ON NUCLEAR PHYSICS
PROCEEDINGS OF THE XXXV INTERNATIONAL WINTER MEETING ON NUCLEAR PHYSICS
BORMIO (IT) 1997
RICERCA SCIENTIFICA ED EDUCAZIONE PERMANENTE SUPPL.110, p.343.
97 107 B

A COMPREHENSIVE STUDY OF MECHANISMS IN REACTIONS INDUCED BY ^6He ON Au AND U

LIENARD E. ET AL.
GANIL - CAEN, LPC - CAEN
INTERNATIONAL WINTER MEETING ON NUCLEAR PHYSICS
PROCEEDINGS OF THE XXXV INTERNATIONAL WINTER MEETING ON NUCLEAR PHYSICS
BORMIO (IT) 1997
RICERCA SCIENTIFICA ED EDUCAZIONE PERMANENTE SUPPL.110, p.507.
97 109 B

SELECTION OF SINGLE-SOURCE MULTIFRAGMENTATION EVENTS FOR COLLISIONS OF $^{155}\text{Gd} + ^{238}\text{U}$ AT 36 MeV/u STUDIED WITH INDRA

FRANKLAND J.D. ET AL.
IPN - ORSAY, GANIL - CAEN, LPC - CAEN, IPNL - VILLEURBANNE, CEN SACLAY - GIF SUR YVETTE,
SUBATECH - NANTES, IPNE IFA - BUCHAREST, NAPOLI UNIV. - NAPOLI, LPN LAVAL UNIV. - QUEBEC
INTERNATIONAL WINTER MEETING ON NUCLEAR PHYSICS
PROCEEDINGS OF THE XXXV INTERNATIONAL WINTER MEETING ON NUCLEAR PHYSICS
BORMIO (IT) 1997
RICERCA SCIENTIFICA ED EDUCAZIONE PERMANENTE SUPPL.110, p.323.
97 110 B

TEMPERATURE MEASUREMENTS FROM RELATIVE POPULATIONS OF EXCITED STATES WITH INDRA

ASSENARD M. ET AL.
SUBATECH - NANTES, CEN SACLAY - GIF SUR YVETTE, IPN - ORSAY, GANIL - CAEN, LPC - CAEN, IPNL - VILLEURBANNE, IPNE IFA - BUCHAREST, NAPOLI UNIV. - NAPOLI, LPN LAVAL UNIV. - QUEBEC
INTERNATIONAL WINTER MEETING ON NUCLEAR PHYSICS
PROCEEDINGS OF THE XXXV INTERNATIONAL WINTER MEETING ON NUCLEAR PHYSICS
BORMIO (IT) 1997
RICERCA SCIENTIFICA ED EDUCAZIONE PERMANENTE SUPPL.110, p.465.
97 112 B

PRESENT AND FUTURE OF RADIOACTIVE BEAMS AT GANIL : NEW TRENDS IN PHYSICS WITH THE FORTHCOMING SPIRAL FACILITY

LEWITOWICZ M.,

GANIL - CAEN

PROCEEDINGS OF 1996 KONAN WORKSHOP ON NUCLEAR PHYSICS

KONAN (JP) 1996

97 61 C

PRESENT AND FUTURE EXPERIMENTS WITH EXOTIC BEAMS AT GANIL/SPIRAL

MUELLER A.C.

IPN - ORSAY

ZEITSCHRIFT FÜR PHYSIKS A358 (1997) 153.

97 64 C

NEUTRON TRANSFER REACTIONS WITH RADIOACTIVE BEAMS

WINFIELD J.S. ET AL.

LPC ISMRA - CAEN, GANIL - CAEN, SURREY UNIV. - GUILDFORD

NIM A396 (1997) 147.

97 67 C

STUDY OF NEUTRON-RICH NUCLEI NEAR THE N = 20 NEUTRON SHELL CLOSURE USING THE ³⁶S BEAM

TARASOV O. ET AL.

FLNR JINR - DUBNA, NPI - REZ, LIVERPOOL UNIV. - LIVERPOOL, LPC - CAEN, GANIL - CAEN, IAP -

BUCHAREST-MAGURELE, IPN - ORSAY

PROCEEDINGS OF THE 8th INTERNATIONAL 8th INTERNATIONAL CONFERENCE ON NUCLEAR REACTION MECHANISMS

CONFERENCE ON NUCLEAR REACTION MECHANISMS

9 Juin 1997

RICERCA SCIENTIFICA ED EDUCAZIONE PERMANENTE SUPPL.111, p.416.

97 91 C

SEARCH FOR ²⁸O AND STUDY OF NEUTRON-RICH NUCLEI NEAR THE N = 20 SHELL CLOSURE

TARASOV O. ET AL.

FLNR JINR - DUBNA, LIVERPOOL UNIV. - LIVERPOOL, LPC ISMRA - CAEN, GANIL - CAEN, IAP -

BUCHAREST MAGURELE, NPI - REZ, IPN - ORSAY

PHYSICS LETTERS B409 (1997) 64.

97 95 C

SHADOWING EFFECTS AND TRANSVERSE MOMENTUM DEPENDENCE OF PARTICLE EMISSION IN INTERMEDIATE ENERGY HEAVY ION COLLISIONS

BUTA A. ET AL.

LPC ISMRA - CAEN, IPNE - BUCHAREST, GANIL - CAEN, NSCL MSU - EAST LANSING

ZEITSCHRIFT FÜR PHYSIKS A357 (1997) 9.

97 02 D

A HOT EXPANDING SOURCE IN 50 A MeV Xe + Sn CENTRAL REACTIONS

MARIE N. ET AL.

GANIL - CAEN, LPC ISMRA - CAEN, IPN - ORSAY, CE SACLAY - GIF SUR YVETTE, IPNL -

VILLEURBANNE, SUBATECH - NANTES

PHYSICS LETTERS B391 (1997) 15.

97 04 D

SURVEYING THE NUCLEAR CALORIC CURVE

MA Y.G. ET AL.

LPC ISMRA - CAEN, CE SACLAY - GIF SUR YVETTE, GANIL - CAEN, IPN - ORSAY, IPNL -

VILLEURBANNE, SUBATECH - NANTES

PHYSICS LETTERS B390 (1997) 41.

97 05 D

ROLE OF ANHARMONICITIES AND NONLINEARITIES IN HEAVY ION COLLISIONS. A MICROSCOPIC APPROACH

LANZA E.G. ET AL.

DIPARTI.DI FIS. AND INFN - CATANIA, DEPARTA.DE FIS.MOL.NUCL. - SEVILLA, GANIL - CAEN

NUCLEAR PHYSICS A613 (1997) 445.

97 06 D

DIRECTED COLLECTIVE FLOW AND AZIMUTHAL DISTRIBUTIONS IN $^{36}\text{Ar} + ^{27}\text{Al}$ COLLISIONS FROM 55 TO 95 MeV/u

ANGELIQUE J.C. ET AL.

LPC ISMRA - CAEN, GANIL - CAEN, IPN UCL - LOUVAIN-LA-NEUVE, LPN - NANTES, DSF AND INFN - NAPOLI, IMP - LANZHOU

NUCLEAR PHYSICS A614 (1997) 261.

97 09 D

ELASTIC SCATTERING AND CHARGE EXCHANGE REACTION WITH LIGHT NEUTRON RICH EXOTIC BEAMS

CORTINA-GIL M.D. ET AL.

GANIL - CAEN, CE SACLAY - GIF-SUR-YVETTE, FOSTER RAD.LAB. Mc GILL UNIV. - MONTREAL, IPN - ORSAY, IFUSP DFN - SAO PAULO, LPC ISMRA - CAEN

PROCEEDINGS OF THE FOURTH INTERNATIONAL CONFERENCE ON RADIOACTIVE NUCLEAR BEAMS

OMIYA (JP) 1996

NUCLEAR PHYSICS A616 (1997) 215c.

97 29 D

^8B STUDIED AS A SECONDARY BEAM AT GANIL

BORCEA C. ET AL.

GANIL - CAEN, IAP - BUCHAREST- MAGURELE, IPN - ORSAY, NPI - REZ, FLNR JINR - DUBNA, IEP WARSAW UNIV. - WARSAW

NUCLEAR PHYSICS A616 (1997) 231c.

PROCEEDINGS OF THE FOURTH INTERNATIONAL CONFERENCE ON RADIOACTIVE NUCLEAR BEAMS

OMIYA (JP) 1996

97 30 D

REACTIONS INDUCED BY BEAMS OF NEUTRON AND PROTON HALO NUCLEI

PENIONZHKEVICH Yu.E.

JINR - DUBNA

NUCLEAR PHYSICS A616 (1997) 247c.

PROCEEDINGS OF THE FOURTH INTERNATIONAL CONFERENCE ON RADIOACTIVE NUCLEAR BEAMS

OMIYA (JP) 1996

97 31 D

FUSION AND BREAKUP AT THE BARRIER WITH UNSTABLE NUCLEI

SIGNORINI C.

DIPART.DI FIS. AND INFN - PADOVA

NUCLEAR PHYSICS A616 (1997) 262c.

PROCEEDINGS OF THE FOURTH INTERNATIONAL CONFERENCE ON RADIOACTIVE NUCLEAR BEAMS

OMIYA (JP) 1996

97 33 D

NEW μ s ISOMERS IN $T_z = 1$ NUCLEI PRODUCED IN THE $^{112}\text{Sn}(63\text{A MeV}) + ^{\text{nat}}\text{Ni}$ REACTION

GRZYWACZ R. ET AL.

IFD WARSAW UNIV. - WARSAW, GANIL - CAEN, IAP - BUCHAREST-MAGURELE, GOTTINGEN UNIV. - GOTTINGEN, FLNR JINR - DUBNA, IPN - ORSAY, GSI - DARMSTADT, LEUVEN UNIV. - LEUVEN, LPC - CAEN, CERN - GENEVE

PHYSICAL REVIEW C55, 3 (1997) 1126.

97 40 D

TWO-PHOTON CORRELATIONS : FROM YOUNG EXPERIMENTS TO HEAVY-ION COLLISION DYNAMICS

MARQUES F.M. ET AL.

GANIL - CAEN, LPC - CAEN, WARSAW UNIV. - WARSAW, KVI - GRONINGEN

PHYSICS REPORTS 284, No.3 (1997) 91.

97 43 D

HIGHEST TEMPERATURES SUSTAINABLE IN HEAVY NUCLEI PRODUCED IN Ar + Au COLLISIONS AT 60 A MeV

LECOLLEY F.R. ET AL.

LPC ISMRA - CAEN, UNIV. LIBRE DE BRUXELLES - BRUXELLES, CRN - STRASBOURG, IPN FNRS - LOUVAIN LA NEUVE

NUCLEAR PHYSICS A620 (1997) 327.

97 58 D

THE $^{12}\text{C} + \alpha$ REACTION RATE FROM THE ELASTIC ^{16}O BREAKUP

KIENER J. ET AL.

CSNSM - ORSAY, CRN - STRASBOURG, GANIL - CAEN, RIKKYO UNIV. - TOKYO, IPN - ORSAY

PROCEEDINGS OF THE FOURTH INTERNATIONAL SYMPOSIUM ON NUCLEI IN THE COSMOS

NOTRE DAME (USA) 1996

NUCLEAR PHYSICS A621, 1-2 (1997) 173c.

97 65 D

HARD PHOTONS AND NEUTRAL PIONS AS PROBES OF HOT AND DENSE NUCLEAR MATTER

SCHUTZ Y. ET AL.

GANIL - CAEN, IFC VALENCIA UNIV. - BURJASSOT, KVI - GRONINGEN, GIESSEN UNIV. - GIESSEN, GSI - DARMSTADT, CENBG - GRADIGNAN, SOLTAN INST. NUCL. STUDIES - SWIERK, NPI - REZ

NUCLEAR PHYSICS A622 (1997) 404.

97 68 D

PROBABILITY OF FISSION INDUCED BY 1.2 GeV ANTIPROTONS

SCHMID S. ET AL.

TECHNISCHE UNIV. MUNCHEN - MUNCHEN, HMI - BERLIN, GANIL - CAEN, WARSAW UNIV. -

WARSZAWA, FORSCHUNGSZENTRUM ROSSENDORF - DRESDEN, CERN - GENEVE, INR RUSSIAN ACAD. OF SCI. - MOSCOW

ZEITSCHRIFT FÜR PHYSIKS A359 (1997) 27.

97 71 D

NEUTRON MULTIPLICITY DISTRIBUTIONS FOR 1.94 TO 5 GeV/c PROTON-, ANTIPROTON-, PION-, KAON-, AND DEUTERON-INDUCED SPALLATION REACTIONS ON THIN AND THICK TARGETS

PIENKOWSKI L. ET AL.

HMI - BERLIN, GANIL - CAEN

PHYSICAL REVIEW C56 (1997) 1909.

97 80 D

UNUSUAL BEHAVIOUR OF FUSION-FISSION AT BARRIER ENERGIES FOR A NEUTRON-RICH HALO NUCLEUS

FEKOU-YOUMBI V. ET AL.

DSM CEA SACLAY - GIF SUR YVETTE, GANIL - CAEN, IPNE - BUCHAREST MAGURELE, IPN - ORSAY,
DIPART. DI FISICA & INFN - CATANIA, IFU - SAO PAULO, IMP - LANZHOU
JOURNAL OF PHYSICS G23 (1997) 1259.
97 81 D

NEAR- AND SUB-BARRIER FISSION-FUSION STUDIES FOR $^{9,11}\text{Be} + ^{238}\text{U}$

FEKOU-YOUMBI V. ET AL.

DSM CEA SACLAY - GIF SUR YVETTE, GANIL - CAEN, IPNE - BUCHAREST, IPN - ORSAY, DIPART. DI FIS.
& INFN - CATANIA, IFUSP - SAO PAULO, IMP - LANZHOU
FRONTIER AND PERSPECTIVE OF NUCLEAR SCIENCE
PROCEEDINGS 7TH FRANCO-JAPANESE COLLOQUIUM
DOGASHIMA (JP) 1996
97 86 D

MULTIFRAGMENT PRODUCTION IN HEAVY ION INDUCED REACTIONS AT INTERMEDIATE ENERGY

DAYRAS R. ET AL.

CE SACLAY - GIF SUR YVETTE, GANIL - CAEN, IPN - ORSAY, LPC - CAEN, SUBATECH - NANTES, IPNL -
VILLEURBANNE
FRONTIER AND PERSPECTIVE OF NUCLEAR SCIENCE
PROCEEDINGS 7TH FRANCO-JAPANESE COLLOQUIUM
DOGASHIMA (JP) 1996
97 87 D

THERMODYNAMICAL EQUILIBRIUM FOR NUCLEAR MATTER PRODUCED IN HEAVY ION COLLISIONS AROUND 100 AMeV ?

BORDERIE B. ET AL.

IPN - ORSAY, LPC ISMRA - CAEN, GANIL - CAEN, IPN LYON - VILLEURBANNE, DAPNIA CEN SACLAY -
GIF SUR YVETTE, SUBATECH - NANTES, INST. OF PHYSICS & NUCLEAR ENG. - BUCHAREST
8th INTERNATIONAL CONFERENCE ON NUCLEAR REACTION MECHANISMS
PROCEEDINGS OF THE 8th INTERNATIONAL CONFERENCE ON NUCLEAR REACTION MECHANISMS
VARENNA (IT) 1997
RICERCA SCIENTIFICA ED EDUCAZIONE PERMANENTE SUPPL.111, p.239.
97 89 D

STUDY OF BINARY COLLISIONS DYNAMICS IN $^{86}\text{Kr} + ^{165}\text{Ho}$ COLLISIONS AT 60 MeV/u WITH THE NEUTRON DETECTOR D  MON

DORVAUX O. ET AL.

INST. DE RECHERCHES SUBATOMIQUES UNIV. LOUIS PASTEUR - STRASBOURG, UNIV. LIBRE DE
BRUXELLES - BRUXELLES, LPC ISMRA - CAEN
8th INTERNATIONAL CONFERENCE ON NUCLEAR REACTION MECHANISMS
PROCEEDINGS OF THE 8th INTERNATIONAL CONFERENCE ON NUCLEAR REACTION MECHANISMS
VARENNA (IT) 1997
RICERCA SCIENTIFICA ED EDUCAZIONE PERMANENTE SUPPL.111, p.336.
97 92 D

ATOMIC EFFECTS IN HEAVY-ION ELASTIC SCATTERING

CASANDJIAN J.M. ET AL.

GANIL - CAEN, INST. DE FIS. DA UNIVERSIDADE DE SAO PAULO - SAO PAULO, INST. DE FISICA UNAM -
MEXICO, DIPART. DI FISICA & INFN - CATANIA, LPC ISMRA - CAEN, IPN - ORSAY, KVI - GRONINGEN
PHYSICAL REVIEW C56 (1997) 2700.
97 96 D

MULTI-FRAGMENT PARTITIONS IN THE 32 TO 95 AMeV $^{36}\text{Ar} + ^{58}\text{Ni}$ REACTIONS

CHARVET J.L. ET AL.

CE SACLAY - GIF SUR YVETTE, IPN - ORSAY, GANIL - CAEN, LPC - CAEN, UOBK - VILLEURBANNE,
SUBATECH - NANTES, IPNE IFA - BUCHAREST, NAPOLI UNIV. - NAPOLI
INTERNATIONAL WINTER MEETING ON NUCLEAR PHYSICS

PROCEEDINGS OF THE XXXV INTERNATIONAL WINTER MEETING ON NUCLEAR PHYSICS
BORMIO (IT) 1997

RICERCA SCIENTIFICA ED EDUCAZIONE PERMANENTE SUPPL.110, p.309.

97 106 D

DEMON AS A NEUTRON PROBE ION HEAVY ION COLLISIONS

DORVAUX O. ET AL.

CRN - STRASBOURG, LPC ISMRA - CAEN, UNIVERSITE LIBRE DE BRUXELLES - BRUXELLES
LARGE-SCALE COLLECTIVE MOTION OF ATOMIC NUCLEI PROCEEDINGS OF THE INTERNATIONAL
CONFERENCE ON LARGE-SCALE COLLECTIVE MOTION OF ATOMIC NUCLEI

MESSINA (IT) 1996

97 120 D

HARD PHOTON INTENSITY INTERFEROMETRY IN HEAVY ION COLLISIONS AT INTERMEDIATE ENERGIES

BADALA A. ET AL.

INFN - CATANIA, DIPART. DI FISICA DELL UNIV. DI CATANIA - CATANIA, INFN LNS - CATANIA

LARGE-SCALE COLLECTIVE MOTION OF ATOMIC NUCLEI

PROCEEDINGS OF THE INTERNATIONAL CONFERENCE ON LARGE-SCALE COLLECTIVE MOTION OF
ATOMIC NUCLEI

MESSINA (IT) 1996

97 122 D

TWO-SLIT INTERFERENCE OF BREMSSTRAHLUNG PHOTONS FROM HEAVY-ION REACTIONS

MARQUES F.M. ET AL.

MARTINEZ G., MATULEWICZ T., OSTENDORF R.W., SCHUTZ Y.

LPC ISMRA - CAEN, GANIL - CAEN

PHYSICS LETTERS B394 (1997) 37.

97 08 E

HIGH TRANSVERSE MOMENTUM PROTON EMISSION IN Ar + Ta COLLISIONS AT 94 MeV/u

GERMAIN M. ET AL.

SUBATECH - NANTES, LPC ISMRA - CAEN, GANIL - CAEN

NUCLEAR PHYSICS A620 (1997) 81.

97 55 E

TOPOLOGY ANALYSIS FOR THE IDENTIFICATION OF ENERGETIC PHOTONS IN A SEGMENTED ELECTROMAGNETIC CALORIMETER

MARTINEZ G. ET AL.

GANIL - CAEN

NIM A391 (1997) 435.

97 66 E

PRODUCTION OF π^0 AND η MESONS IN CARBON-INDUCED RELATIVISTIC HEAVY-ION COLLISIONS

AVERBECK R. ET AL.

GSI - DARMSTADT, FRANKFURT UNIV. - FRANKFURT AM MAIN, GIESSEN UNIV. - GIESSEN, KVI -
GRONINGEN, GANIL - CAEN, NPI - PRAHY, IFC - BURJASSOT

Z. PHYS. A359 (1997) 65.

97 70 E

FAST PARTICLE EMISSION IN INELASTIC CHANNELS OF HEAVY-ION COLLISIONS

SCARPACI J.A. ET AL.

IPN - ORSAY, GANIL - CAEN, KVI - GRONINGEN

8th INTERNATIONAL CONFERENCE ON NUCLEAR REACTION MECHANISMS

PROCEEDINGS OF THE 8th INTERNATIONAL CONFERENCE ON NUCLEAR REACTION MECHANISMS

VARENNA (IT) 1997

RICERCA SCIENTIFICA ED EDUCAZIONE PERMANENTE SUPPL.111, p.351.

97 90 E

EXCLUSIVE π^0 - AND η -MESON PRODUCTION IN $^{40}\text{Ar} + ^{nat}\text{Ca}$ AT 800 A MeV

MARIN A. ET AL.

IFIC UNIV. DE VALENCIA - BURJASSOT, GSI - DARMSTADT, GANIL - CAEN, LPC - CAEN, GIESSEN UNIV.

- GIESSEN, KVI - GRONINGEN, NPI - REZ, RES.INST. FOR PART. & NUCL. PHYS. - BUDAPEST

PHYSICS LETTERS B409 (1997) 77.

97 94 E

CONTRIBUTION OF π^0 AND η DALITZ DECAYS TO THE DILEPTON INVARIANT-MASS SPECTRUM IN 1A GeV HEAVY-ION COLLISIONS

HOLZMANN R. ET AL.

GSI - DARMSTADT, GIESSEN UNIV. - GIESSEN, GANIL - CAEN, IFC - BURJASSOT, FRANKFURT UNIV. -

FRANKFURT, NPI - REZ, KVI - GRONINGEN

PHYSICAL REVIEW C56 (1997) R2920.

97 116 E

PROBING THE PRE-EQUILIBRIUM STAGE IN HEAVY ION COLLISIONS WITH HARD PHOTONS AND ENERGETIC PROTONS

SAPIENZA P. ET AL.

INFN LNS - CATANIA, IPN - ORSAY, DAPNIA CE SACLAY - GIF SUR YVETTE, GANIL - CAEN

LARGE-SCALE COLLECTIVE MOTION OF ATOMIC NUCLEI

PROCEEDINGS OF THE INTERNATIONAL CONFERENCE ON LARGE-SCALE COLLECTIVE MOTION OF ATOMIC NUCLEI

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**D) - INTERDISCIPLINARY
RESEARCH**

1 - BASIC COLLISION PROCESSES

Search for Resonant Trielectronic Recombination in Channeling Conditions

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During the experiment P372 we have tried to observe the resonant trielectronic recombination by heavy ions. This process, occurring during the collision of the ion with electrons, is the equivalent of the Resonant Transfer and Double Excitation (RT2E) for ion-atom collisions: the capture of a target electron by a projectile having at least two initial electrons is accompanied by the simultaneous excitation of these two electrons. For instance, capture into the L-shell of a He-like incoming projectile would lead to the formation of a Li-like ion with a double K-hole and all electrons in the L-shell. For sufficiently high Z ions, like Kr^{34+} in our experiment, this triply excited state is expected to decay radiatively.

Theoretical estimates give the probability of the time-reverse process (KK-LLL "double" Auger) to be less than 10^{-6} times that for the single KLL Auger process. Then we expect a similar ratio between probabilities for trielectronic recombination and the well-known dielectronic recombination, already studied at GANIL by our collaboration.

Ion channeling in a crystal has two main advantages for observing such a low cross section capture process: first, channeled ions experience a dense quasi-free electron gas, and, second, close collisions with target atomic cores are strongly attenuated, which lowers the experimental background.

The expected signature of the trielectronic recombination was the observation of two $K\alpha$ photons resulting from the decay of the triply excited state, in coincidence with the detection of a channeled Kr^{33+} ion, as a function of the incident beam energy around the resonance (37.4, 40.6 and 42.3 AMeV). The experiment was performed in the SPEG beam line, allowing a very high energy resolution of transmitted ions through a thin crystal. In order to optimize the sensitivity and minimize the background, an ion per ion detection was performed at $3 \cdot 10^6$ incoming projectiles per second.

We obtain an upper limit of the cross section in the millibarn range, which represents an improvement of nearly two orders of magnitude over the result of a previous ion-gas experiment.

The first results are presented at the HCI-98 conference (Bensheim, sept.98)

Single and Multiple Excitation Processes in Heavy Ion-Atom Collisions at Intermediate Velocity

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The knowledge of the processes involved in swift heavy ion-atom collisions can be considered as the first step in the understanding of ion-matter interactions. This picture corresponds to a given description of the projectile stopping power. In this respect, the intermediate velocity regime ($v_p \approx v_e$, where v_p is the projectile velocity and v_e the mean orbital velocity of the active electron) is of particular interest : the ion stopping power is nearly maximum and for applied purposes, the understanding of mechanisms accounting for radiation damage in materials is important. However, in this velocity range, experimental determination of monoelectronic process cross sections is not so simple since the excitation, ionization and capture channels are of the same order of magnitude and may influence each other strongly. On the other hand, the role of target electrons as active partners, via *capture channel coupling* and *direct target electron-projectile electron interaction*, is not well known. So far, these effects are not taken into account even by the most sophisticated theories. Furthermore, multiple processes, involving more than one electron of the projectile and of the target as well, are actually under study and ask for much debated questions.

Using high resolution x-ray spectroscopy, we have measured cross sections of single as well as of multiple projectile electron excitations when a two-electron Ar^{16+} ion collides with neutral target atoms. For a fixed impact velocity ($v_p = 23$ a.u.), but using various targets (He, N_2 , Ne, Ar, Kr and Xe), we have investigated a range of interactions spanning from *the perturbative regime to the strong interaction regime*. More precisely, we have determined cross sections of capture-ionization (CI), capture excitation (CE), capture-excitation-ionization (CEI), double excitation (DE), excitation-ionization (EI) and single excitation (SE) (see table 1).

Initial state	Processes involving only projectile electrons		Processes involving also target electrons	
	Processes	Final states	Processes	Final states
$\text{Ar}^{16+}(1s^2\ ^1S_0) + X$	SE	$\text{Ar}^{16+}(1snp\ ^1P) + X$	CI	$\text{Ar}^{16+}(1s2p\ ^1P\text{ and }^3P) + X^+$
	DE	$\text{Ar}^{16+}(2l2l'\ ^1L) + X$	CEI	$\text{Ar}^{16+}(2l2l'\ ^1L\text{ and }^3L) + X^+$
	EI	$\text{Ar}^{17+}(2p,3p) + X$	CE	$\text{Ar}^{15+}(1s2l2l'\ ^2L\text{ and }^4L) + X^+$

Table 1 : Review of all the processes studied (see text) ; the quoted final states are those observed experimentally

The experiment has been performed on the SME facility. A high intensity beam ($1\ \mu\text{A}_e$) of Ar^{16+} at 13.6 MeV/u was directed at various atomic targets in an open gaseous cell. The specially designed spectrometer used was composed of a flat mosaic graphite crystal and a localization chamber. Its global efficiency amounted to 1.3×10^{-7} ($\pm 15\%$) and the resolving power reached was 1.4×10^{-3} around 3.7 keV. Spectra we have obtained, presented in Fig.1 in the case of N_2 and Xe targets, allow to distinguish all the processes involved: in particular, we achieve "spin-selectivity" (i.e. triplet and singlet components are well separated).

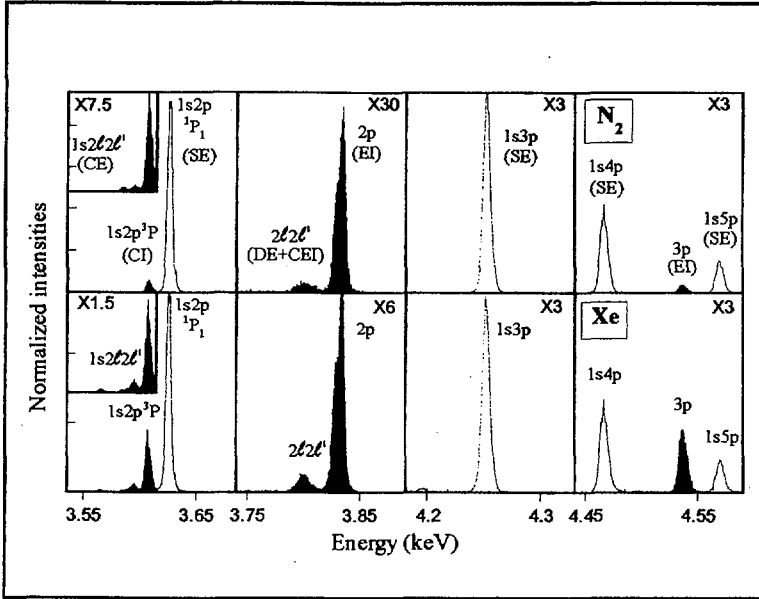


Figure 1 : X-ray spectra recorded with the crystal spectrometer in the case of Ar^{16+} colliding with N_2 and Xe neutral targets. For each target, intensity of the transitions have been normalized to $1s2p \ ^1P_1 \rightarrow 1s^2 \ ^1S_0$ –the spectra recorded for the N_2 and Xe targets have independent normalization. The transitions filled in black are the lines due mainly to multiple processes.

We have extracted cross sections for each of these processes and the main results may be summarized as follow:

- The evolution of single excitation cross sections, $\sigma_{\text{SE}}^{\text{np}}$ (up to $n=5$), for a given projectile, fulfills a scaling law: $\sigma_{\text{SE}}^{\text{np}} \approx C_{\text{SE}}(Z_t) \times Z_t^2$ (see Fig.2), where $C_{\text{SE}}(Z_t)$ is a n —independent coefficient (clearly less than 1). Most recent theoretical predictions are in agreement with this evolution. Nevertheless the quantitative values still off by almost a factor of 2 compared to experiment. This disagreement may be assigned to target electron role which is not well taken into account.
- The cross sections of multiple processes involving both target electrons –via capture channels- and projectiles ones, increase more rapidly with Z_t than those involving only projectile electrons (see Fig.3). In particular, the capture+ionization process cross section, negligible for He target, reaches 54% of the single excitation one for Xe. Those very first measurements performed for a heavy ion bring into light the importance, in the intermediate regime, of these often neglected processes.
- As electron correlations in the initial state can be neglected, a simple independent electron model appears to be successful for predicting the evolution of multiple processes involving only projectile electrons (namely DE and EI cross sections).

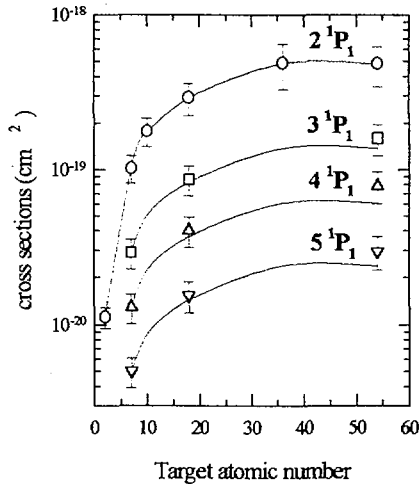


Figure 2: single excitation cross sections $1s^2 \rightarrow 1snp$ up to $n=5$, for $\text{Ar}^{16+} \rightarrow Z_t$ collisions (full lines correspond to the scaling law (see text)).

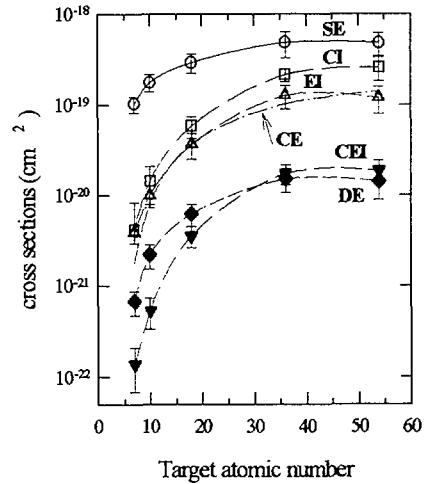


Figure 3: single and multiple processes cross sections in $n=2$ for $\text{Ar}^{16+} \rightarrow Z_t$ collision.

References for published works:

- Adoui L 1995 *Thèse de doctorat* Université Pierre et Marie Curie, Paris
 Adoui L et al. 1995 *Nucl. Instr. and Meth. in Physics Research B* **98** 312
 Vernhet D et al 1996 *Nucl. Instr. and Meth. in Physics Research B* **107** 71
 Vernhet D 1997 *Nouvelles du GANIL* **60** 9
 Vernhet D et al 1997 *Phys. Rev. Lett.* **79** 3625

Production and Transport of Projectile Excited States in Solids

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Two different types of descriptions can be used to calculate the slowing down of a projectile through materials. For both approaches, improvements towards fully *ab initio* calculations are attempted by several groups while, in the past, the prediction of stopping power of heavy ions had to rely on the use of "free parameters" like the effective nuclear charge of the projectile. The first description assumes that ion-solid interaction is the result of a series of binary collisions with the target electrons. In this collisional picture, the evolution of charge state distributions of the projectile at the exit of solid targets, involving core state populations, can be successfully predicted in many cases (like for the ETACHA code). In the other one (the dielectric theory), the target electrons are considered to respond collectively to the passage of the projectile. The polarization of the medium can be described as a wake of electronic density fluctuation trailing the ion. The gradient of the wake potential defines an electric field responsible for the stopping power. This electric field also acts directly on the excited levels of the projectile and will induce, among other effects, binding energy shifts as well as Stark mixing of substates. Until recently, only "quasi-free" target electrons were considered in this approach. Up to now, it exists in fact very few experimental results that can be used to decide which of these pictures is the most appropriate and to define eventually their validity limits. In particular, tests on the predictions of the wake model concerning the spatial extension of the electronic density fluctuations are needed. Atomic physics experiments can be used to shed some light on ion-matter interaction. Looking at one partner of the collision, namely the excited state populations of the projectile, the response of the material may be probed.

Experimental studies on the production and transport of core and Rydberg states have been done for Ar¹⁸⁺ ($v=23$ a.u.) on C and Kr³⁶⁺ ($v=36$ a.u.) on C and Cu with target thicknesses ranging from 3.5 to 200 $\mu\text{g}/\text{cm}^2$. The determination of Ar¹⁷⁺ and Kr³⁵⁺ $n\ell$ excited states populations has been performed using x-ray spectroscopy techniques on SME and LISE facilities. The Rydberg state populations are measured through long life time deexcitation of Lyman line transitions ($np \rightarrow 1s$), while core state populations are determined looking at prompt emission lines of the projectile.

Two models, relevant to a collisional approach, have been simultaneously developed to describe the transport of projectile excited states in solid targets. Both use the Continuum Distorted Wave cross sections to calculate the production of « initial » $n\ell$ states populated by the primary capture process. The transport of these states is then described either by a rate equations model (using Plane Wave Born Approximation calculations for excitation and ionization cross sections) or a Monte Carlo simulation of classical dynamics.

A comparison with experiments shows that:

- both collisional approaches allow to interpret the Rydberg ℓ state populations (see Fig. 1). Long life time population measurements for the thinnest as well as for the thickest target are well reproduced by the classical transport model. The discrepancy with the rate equations model, in the case of the 201 $\mu\text{g}/\text{cm}^2$ carbon target, may be assigned to the number of n -states included so far (indeed, the main limitation of this model is the number of cross sections we are able to calculate).

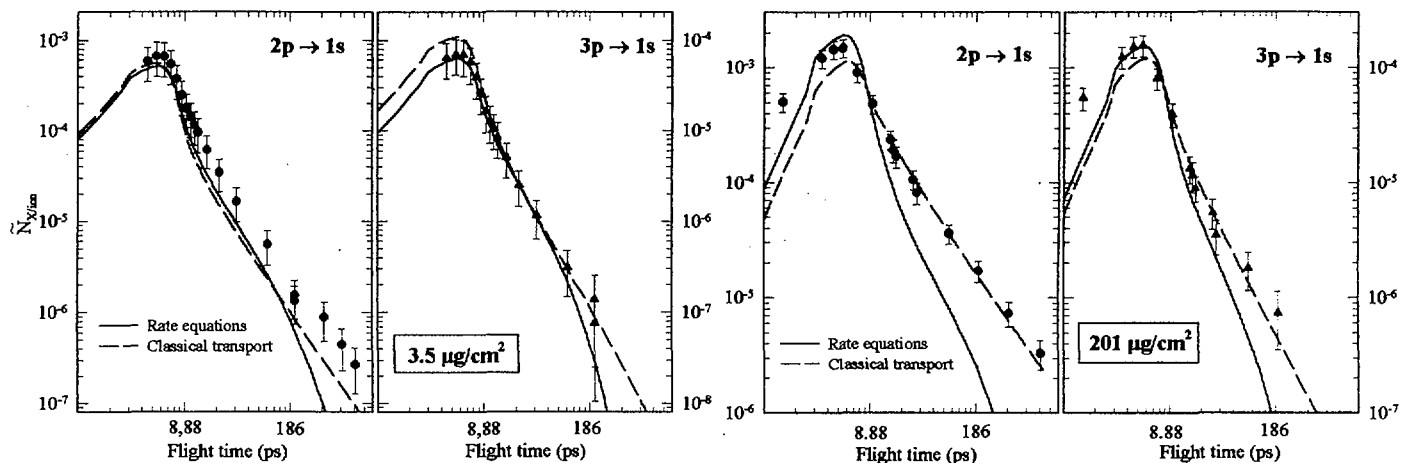


Figure 1: Comparison between collisional models and experiment for Rydberg state populations (namely large flight time of $2p \rightarrow 1s$ and $3p \rightarrow 1s$ transitions) in the case of $Ar^{16+} \rightarrow C$ at $v = 23$ a.u.

- “pure” collisional picture fails to describe the populations of core states ($n=2,3,4$). An illustration of this result (Fig.2) is given by the evolution of the relative populations in $3\ell j$ excited substates of Kr^{35+} ion with carbon target thickness. The Stark beats, experimentally observed, with the ion transit time (i.e. target thickness) is a direct signature of the collective response of the medium: the model, which takes into account the wake-field induced by the Kr^{36+} ion going through the material, gives much better agreement with experiment.

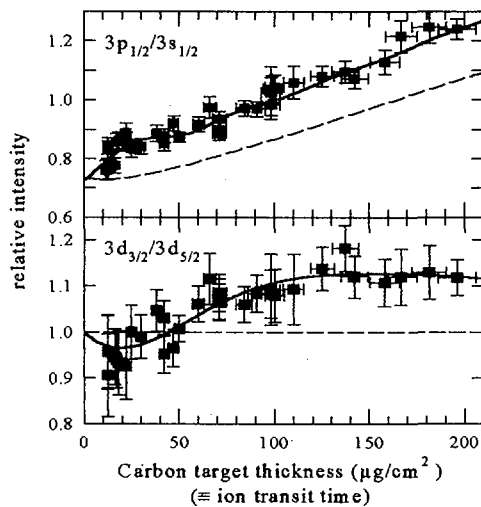


Figure 2: Evolution of relative populations in $3\ell j$ substates of Kr^{35+} ion with carbon target thickness (dashed line: collisional model; full line Stark model).

and generally used in the *dielectric* theory ii) the wake field value corresponding to the *total stopping power*, F_{st} . Measurements in the case of copper are in agreement with an electric field 5 times larger than F_v but correspond to the total stopping power F_{st} . These experimental evidences have already triggered theoretical investigations. Recent calculations go beyond the uniform electron gas model and show that the effect of deeply bound target electrons should be taken into account as non-homogeneities in the jellium.

References for published works:

Lamour E 1997 Thèse de doctorat Université de Caen
 Rozet J-P et al 1996 *Nucl. Instr. And Meth. In Physics Research B* **107** 67
 Vernhet D et al 1998 *J. Phys. B.* **31** 117
 Lamour E et al 1998 *J. Phys. B.* (to be published)

Target	F_{exp}	F_v	F_{st}
Carbon	0.9 ± 0.1	1	1
Copper	3.3 ± 0.3	0.65	3

Table 1: Comparison between experimental electric field values F_{exp} and theoretical ones : F_v corresponds only to the contribution of valence electron of the target, F_{st} corresponds to the total stopping power of the projectile Kr^{36+} ion. Values are given in 10^9 V/cm.

The values of the electric field are directly related to the Stark beat frequency and to the asymptotic value reached for the largest ion transit time. Extracted values from our experimental data are reported in Table 1 and compared to : i) the wake field value F_v , corresponding to valence electrons *only*,

Two- and three-body effects in single ionization of Li by 95 MeV/u Ar^{18+} projectiles:

Analogies with Photoionization

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Cross sections for single electron emission have been measured in collisions of 95 MeV/u Ar^{18+} projectiles with atomic Li for electron energies ranging from 5–1000 eV and angles ranging from 25° – 155° [1]. Because of the high projectile velocity it was possible to separate two- and three-body processes in the angular distributions of the ejected electrons. A comparison the experimental results with theoretical data are shown in Fig. 1.

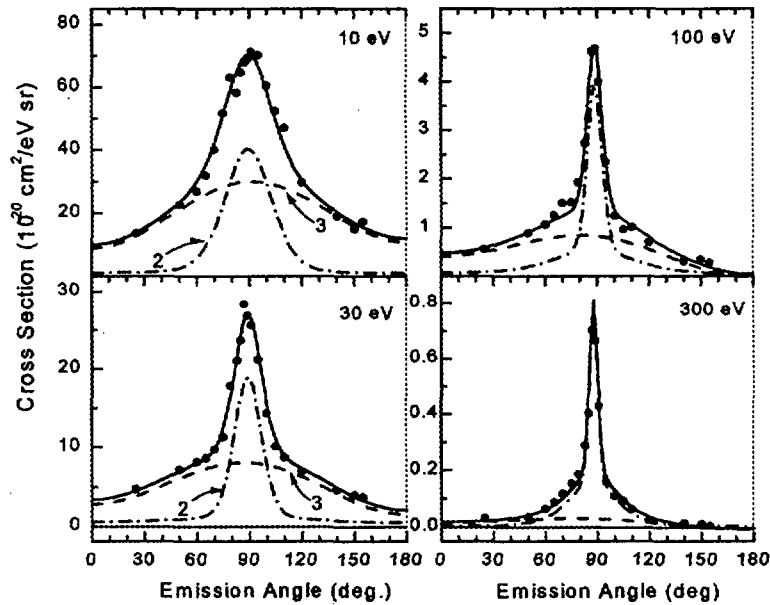


Fig. 1. Angular distributions of electrons emitted at energies of 10, 30, 100, and 300 eV. The dot-dashed curve labeled 2 refers to calculations using the two-body theory [1]. The dashed curve labeled 3 is a fit to the underlying three-body part represented by the function $A + B \sin^2 \theta + C \cos \theta$

A detailed analysis by means of theoretical results shows that the low-energy emission of the 2s electrons is significantly affected by two-body interactions and, furthermore, the node in the Li 2s wave function is seen to manifest itself in the emitted electron spectrum. The emission of the 1s electron is attributed mainly to three-body effects. The two- and three-body processes are associated with Compton scattering and photoabsorption, respectively.

[1] N. Stolterfoht et al., Phys. Rev. Lett. **80**, 4649 (1998)

Electron angular distributions as a function of momentum transfer in double ionization of helium by 100 MeV/u C⁶⁺ impact

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Double ionization of helium has been a much researched topic because helium is the simplest, but not yet fully understood correlated electron system. Double ionization of this two-electron system is an effective probe of correlation effects. In recent times it has become possible to perform kinematically complete ionization experiments with arbitrary projectiles using the specially developed ion and electron momentum spectrometer, the “reaction microscope” (see [1] and references therein). The momentum components of all ionization products: e⁻, e⁻, He²⁺ can be determined from their position and time of flight spectra, and the precisely known, extremely homogenous electric and magnetic fields in the spectrometer. Thus, every double ionization event is mapped onto a point in the nine-dimensional momentum space. From this map it is possible to determine various differential cross-sections.

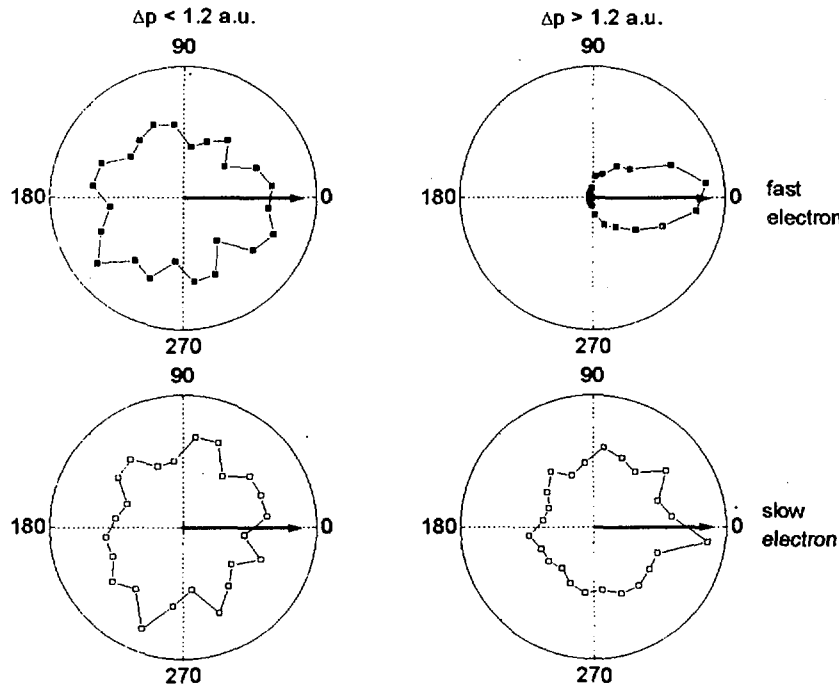


Figure 1: The azimuthal angular distributions of the fast and the slow electrons ejected in the collision $\text{C}^{6+} + \text{He} \rightarrow \text{He}^{2+} + 2\text{e}^-$ for different momentum transfers Δp , as indicated. The arrow represents the direction of momentum transfer to the target in the azimuthal plane. The projectile beam axis is perpendicular to this plane.

The experiments at GANIL were done with 100 MeV/u C^{6+} ions. The projectile-target interaction strength Z_p/v_p , in atomic units, is approximately 0.1. For this interaction strength, one expects similarities between photoionization and ion-impact ionization [2,3]. However, there is one important difference between the two processes, which is that momentum transfer in the former is negligible, whereas in the latter any finite momentum transfer is possible. With this point in mind, angular distributions of ejected electrons in double ionization were studied as a function of the momentum transferred by the projectile to the atom.

Preliminary analysis suggests that the events may be separated into two domains, depending on whether the momentum transfer from the projectile to the target atom is less than or greater than 1.2 a.u. This is clearly seen in the azimuthal angular distributions of the electrons shown in the figure. This critical value is close to the mean momentum of the electron in the ground state of the helium atom, and demarcates soft, indirect ionization and hard, direct ionization. Attempts are also on to identify signatures of two-step and shake-off mechanisms of double ionization.

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- [1] J. Ullrich, R. Moshhammer, R. Dörner, O. Jagutzki, V. Mergel, H. Schmidt-Böcking and L. Spielberger, *J. Phys. B* **30** 2917 (1997)
 - [2] M. Inokuti, *Rev. Mod. Phys.* **43** 297 (1971)
 - [3] R. Moshhammer et. al., *Phys. Rev. Lett.* **79** 3621 (1997)

FAST ELECTRON SPECTRA FROM SWIFT HEAVY ION IMPACT ON SOLIDS

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Fast electron velocity spectra have been measured with the multidetector ARGOS (mounted in the NAUTILUS scattering chamber at GANIL) in a large angular range for atomic collisions induced by 77 MeV/n Ar¹⁸⁺ beam on Al target (Experiment E230a, Nov. 1996) [1]. The velocity of electrons can be determined by the time-of-flight method. An example is shown in fig.1, where the measured intensity of emitted electrons is plotted as a function of the electron velocity taken at two different emission angles. One observes a broad peak from a binary collision between the projectile and a target electron (Binary Encounter Electrons, BEE). In beam direction (0 deg.), this peak should be observed at nearly twice the projectile velocity. As can be seen from fig.1, at small emission angles in forward direction, the shape of the BEE peak is well described by a recent relativistic theory [2] (the calculation is shown as full circles in fig. 1). The broadening of the peak at large emission angle is due to the transport of electrons through the solid foil (energy loss and angular scattering). Also, the angular dependence of the emission cross section is in good agreement with this theory and is close to what one would expect from a simple two body Rutherford ("Billiard Ball") scattering if relativistic kinematics are taken into account. Nevertheless, an important shift of the measured peak towards lower velocities is observed. This can be seen from fig. 2, which shows the position of the maximum of the BEE peak as a function of the emission angle in comparison to the theory. This result is not yet understood. Another interesting result concerns backward emission, where evidence for an excess of fast electrons is found. This can also be seen in fig. 2 which shows the "center of mass" of the fast electron distribution in backward direction.

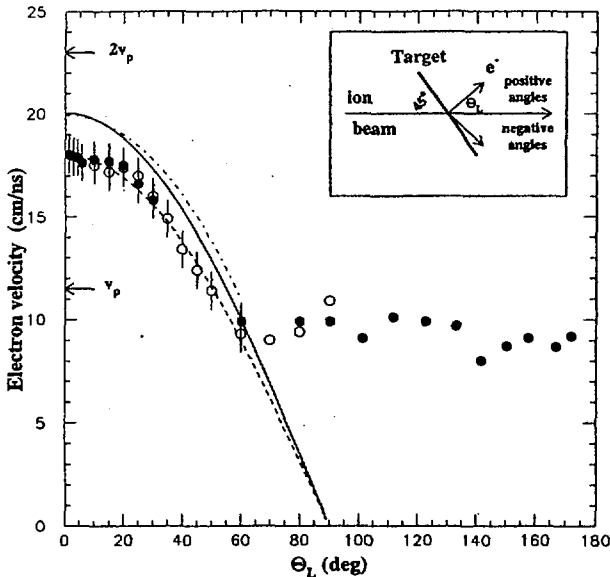


Fig. 2

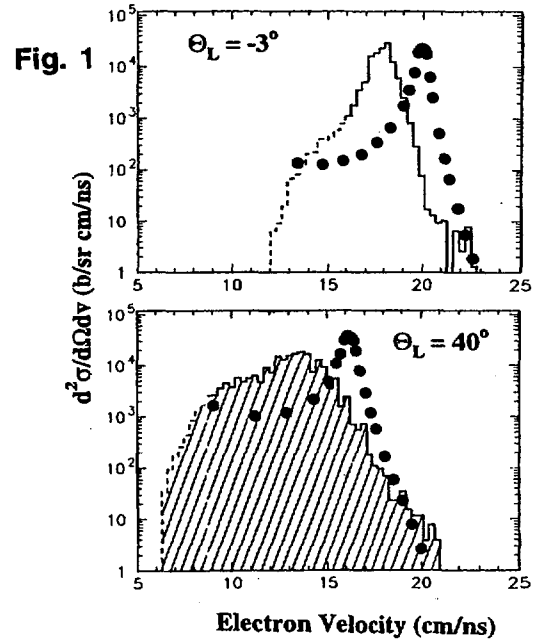


Fig. 1

- [1] G. Lanzanò, E. DeFilippo, S. Aiello, M. Geraci, A. Pagano, G. Politi, S. Cavallaro, F. LoPiano, E.C. Pollacco, C. Volant, S. Vuillier, C. Beck, D. Mahboub, R. Nouicer, H. Rothard, D.H. Jakubassa-Amundsen, submitted to Phys. Rev. A (1998)
[2] D.H. Jakubassa-Amundsen, J. Phys. B.: At. Mol. Opt. Phys. 30 (1997) 365

SOLID STATE EFFECTS IN BINARY ENCOUNTER ELECTRON EMISSION

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Binary encounter electrons (BEE) stem from a basic ionisation mechanism: the collision of a swift projectile with target electrons which should be ejected with an emission angle θ dependent velocity of $v_{BE} = 2 v_p \cos(\theta)$ if the interaction with the target nucleus, binding energy and relativistic effects are neglected (v_p : projectile velocity). The observed BEE peak at fixed angle is a distribution centred near v_{BE} which reflects the initial momentum distribution of the bound target electrons ("Compton profile"). BEE emission from thin foils was studied experimentally at GANIL/SME with Ar^{17+} of 13.6 MeV/u by means of a magnetic spectrometer [1,2,4] (P299). The results were compared to a theory based on the electron impact approximation (EIA) [3,4], where ionisation takes place via electron transfer to the projectile continuum. The active electron scatters elastically from the projectile field. The corresponding cross section is then folded with the Compton profile. A comparison of experiment and theory (solid line) is shown in figs.1,2 for Carbon foils. The BEE peak shape is well described by theory at small emission angles up to 20° . With increasing emission angle, for the thinnest C foils ($d = 4.4 \mu\text{g}/\text{cm}^2$, less than 260 \AA), a shift of the maximum of the BEE peak to lower energies a peak broadening are observed (fig.2). This is due to transport effects (energy loss and angular scattering of electrons in the solid). The importance of such effects can be investigated by increasing the target thickness (fig.1). The overall intensity increases, the maximum shifts to lower energies and the BEE peak finally evolves into a broad distribution without pronounced maximum. The target dependence of BEE emission is discussed in detail in ref. [4].

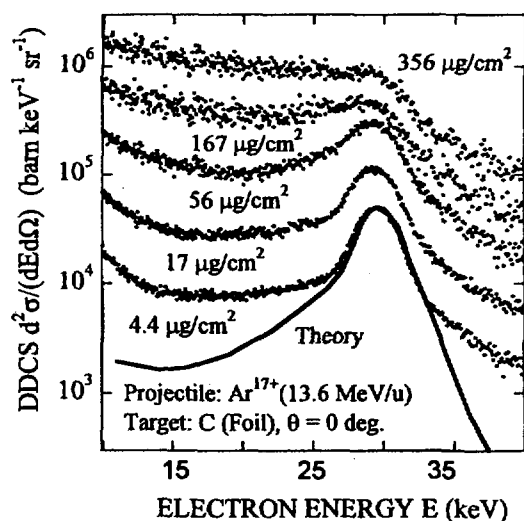


Fig. 1

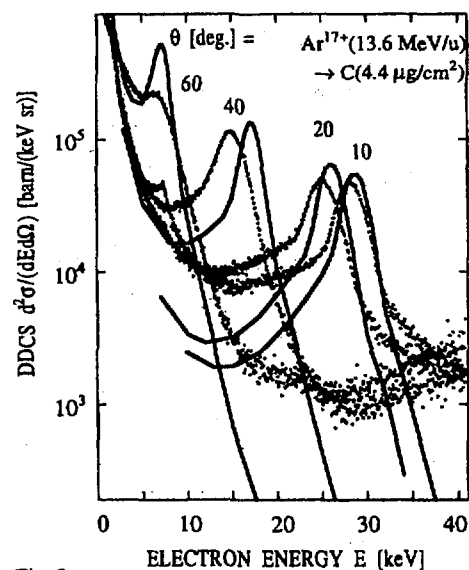


Fig.2

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ELECTRON YIELDS AS PROBE OF SWIFT HEAVY ION-SOLID INTERACTION

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A major part of the energy loss of swift heavy ions in matter leads to excitation and ionisation. From an atomic physics point of view, excitation and ionisation are among the most fundamental consequences of energetic atomic collisions. On the other hand, radiation effects due to electronic energy deposition in condensed matter are closely related to the subsequent electron transport (and secondary electron cascade multiplication) where the deposited energy is distributed along and around the ion track. Finally, after relaxation and thermalisation, the energy initially deposited in electronic excitation may result in creation of defects, nuclear tracks, damage and modification of material properties. A fraction of the electrons is ejected from the solid surface and kinetic electron emission is thus an important probe for the interaction of swift heavy ions with solids. Within the proposals P299, P340 and P395, electron yields (the mean number of electrons γ emitted per ion) were studied as a function of the projectile velocity E_p , the ion charge q and atomic number Z_p at GANIL-LISE and GANIL-SME [1-4]. These experiments are based on current measurements as described in detail in [2]. Varying the target thickness (thin foils) allows in particular to study the evolution of electron emission from single collisions (as in atomic collisions with low density gas targets) up to multiple collisions (as in the bulk of solids, where electron transport phenomena become important) [2]. Specific effects can be observed with heavy ions due to the high charge states inside solids involved, resulting high ionisation cross sections, strong induced perturbation and large electronic energy loss [3,4].

The dependence of electron yields on foil thickness is shown in fig.1 for Cu ions of 9.6 MeV/u, and for Ni ions of 74 MeV/u ($q = 28$ in both cases). Forward yields γ_f evolve over a large thickness range (up to 0.5 mg/cm² at 9.6 MeV/u and 3 mg/cm² at 74 MeV/u). This is caused by secondary electron production (cascade multiplication) by fast primary electrons. Most of these high energy electrons are emitted in forward direction. Electron transport can be studied quantitatively by an analysis of measured electron yields as a function of foil thickness within the framework of an empirical theory described in detail in [2]. It is found that the diffusion length of low energy electrons ($E < 100$ eV) does not depend on the ion species or projectile energy and is of the order of 30 Å. In contrast, the attenuation length of fast electrons ($E \gg 100$ eV) increases strongly with increasing projectile velocity and can be described by a power law $\lambda[\text{Å}] = 390 (E_p/M_p[\text{MeV/u}])^{1.22}$. This explains the "velocity effect": damage in solids is different for fixed electronic energy loss dE/dx , but different ion velocity. Energy is taken away from the track core by fast electrons for faster ions and the density of energy deposition close to the ion track is different. The mean energy $\langle E \rangle$ of ejected electrons increases with E_p/M_p as $\langle E \rangle[\text{eV}] = 92.5 (E_p/M_p[\text{MeV/u}])^{1.08}$.

It is often assumed that electron yields are proportional to the electronic energy loss per unit path length dE/dx and thus it is common practice to compare electron yields to dE/dx by defining a ratio $\Lambda_T = \gamma_T/(dE/dx)$ if total yields ($\gamma_T = \gamma_f + \gamma_b$) are concerned. The energy dependence of Λ_T for H, C, Ni (Cu) and U ions (as shown in fig.2) can be described by a power law: $\Lambda_T = C (E_p/M_p)^n$ as indicated by the solid lines in fig.2. The inset shows the projectile dependence of the exponent n . From fig. 2, one can easily estimate electron yields for all ions in a wide energy range above the maximum of the stopping power curve. This may be useful for the design of ion beam detectors based on secondary electron emission. For proton

Fig. 1: Forward (squares) and backward (circles) electron yields (γ_F, γ_B) obtained with Cu^{28+} (9.6 MeV/u, full symbols) and Ni^{28+} (74 MeV/u, open symbols) as a function of carbon target thickness d . ($1 \mu\text{g}/\text{cm}^2$ corresponds to about 61 \AA for a carbon foil density of $\rho = 1.65 \text{ g}/\text{cm}^3$).

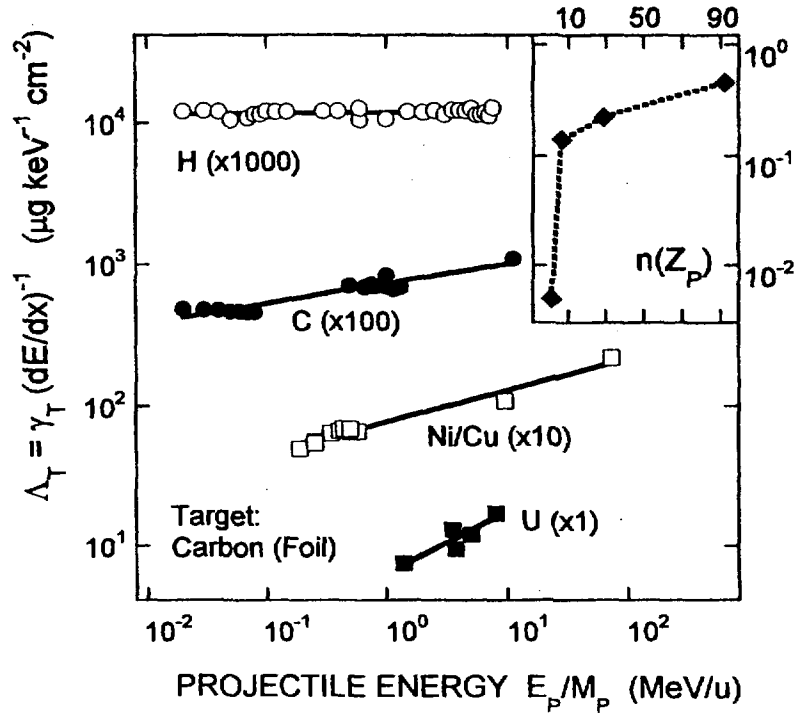
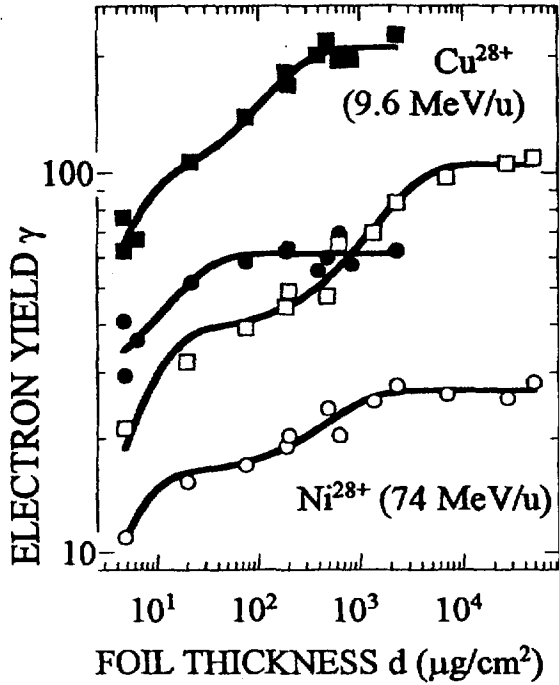


Fig. 2: The ratios of total electron yields and electronic energy loss per unit path length $\Lambda_T = \gamma_T / (dE/dx)$ as a function of the projectile energy E_p/M_p for different ions (the data were multiplied by the indicated factors). The target thickness was chosen so that electron yields have reached the (velocity dependent) asymptotic equilibrium value (see fig. 1, typically $400 \mu\text{g}/\text{cm}^2$ at 10 MeV/u) and the charge state of the incoming ions was chosen close to the mean final charge.

impact, Λ_T is constant over the whole investigated energy range. In contrast, for C ions, a slight increase is observed. For the heavy Cu and Ni ions, the increase of Λ_T with energy is more pronounced and even slightly stronger for U ions. We note that a strong/forward backward asymmetry with increasing Z_p of electron yields was observed and refer the reader to ref. [4] for a detailed discussion.

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Enhancement of dielectronic processes in $\text{Ne}^{10+} + \text{He}$ collisions at energies as low as 1 keV

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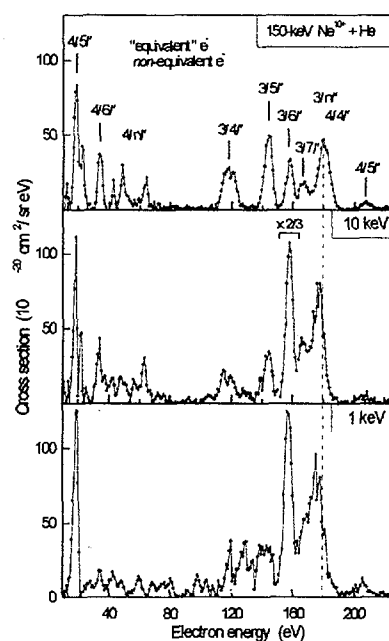
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The method of high-resolution Auger spectroscopy was used to study mechanisms for double-electron capture producing the projectile configurations $3lnl'$ and $4lnl'$ ($n \geq 4$) in $\text{Ne}^{10+} + \text{He}$ collisions. Emphasis was given to slow collisions with projectile energies near 1 keV. At low collision energies the production of the configurations $3lnl'$ ($n \geq 6$) is found to be dominant. It is shown that dielectronic process produced by electron-electron interaction play a major role in the creation of the Ne^{8+} ($3lnl'$) states.



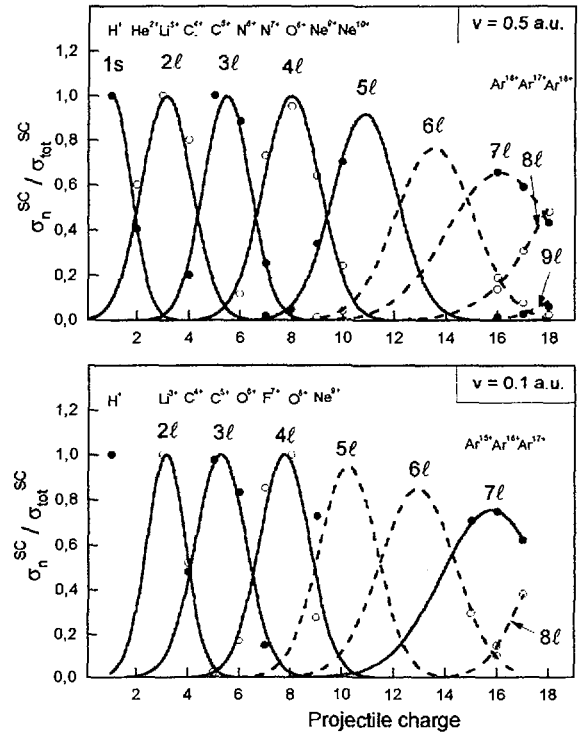
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**Scaling laws for single and double electron capture in $A^{q+} + \text{He}$ collisions ($q \geq Z_A - 2$)
at low impact velocities.**

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We present empirical scaling laws, as a function of projectile charge state, for single and double electron capture in slow collisions between highly charged ions and He atoms at impact velocities of 0.1 and 0.5 a.u. The fitting parameters are shown to be suitable for predicting the populated states in single and double electron capture. The scaling law for single capture is found to be nearly independent of the projectile velocity in the range from 0.1 to 0.5 a.u. The same fitting procedure is followed for double electron capture at the velocity of 0.5 a.u., since independent monoelectronic transitions, due to electron-nucleus interactions, are dominant. At this velocity, the scaling law for the projectile-charge dependence of double-electron capture cross sections is found to be similar to that for single electron capture. At the lower velocity of 0.1 a.u., where dielectronic processes caused by electron-electron interaction gain importance, the charge dependence of double capture cross sections is strongly modified.



Experimental cross sections for producing a given n -state as a function of the projectile charge in $A^{q+} + \text{He}$ collisions. Gaussian curves (solid lines) are used to fit the experimental data. Dashed Gaussian lines extrapolate experiment for n values larger than 5. Experiments using C^{6+} , N^{7+} , O^{8+} , Ne^{10+} and Ar were performed at GANIL.

F. Frémont, C. Bedouet, J.-Y. Chesnel and X. Husson, Phys. Rev. A **57**, 4379 (1998)

Investigation of charge exchange reactions at low energy by recoil ion momentum spectroscopy

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In low energy ion-atom collisions (i.e., projectile speeds smaller than the target electron speed), the dominant target removal process is electron capture. Such collision processes are central to the understanding of fusion plasma or for laser development and for diagnostics of astrophysical photoionized plasmas.

Up to now, such processes were studied through the information carried by the scattered projectile either by energy gain or by photon and electron spectroscopy. Unfortunately, these methods are not direct and are affected by post-collisional effects. It is the reason why we use recoil ion momentum spectroscopy to extract the information carried by the recoiling target. In this way, we perform cinematically complete experiments which give us a picture of the very first moment of the collision without any post collisional perturbation.

Several experiments were carried out with various projectiles delivered by the 14 GHz ECR source at the GANIL's test bench. For the first time in the scientific community we have obtained accurate differential state-selective cross-sections for capture reactions where fully stripped ions such as argon were used as projectiles [1].

The good resolution obtained in scattering angle and in Q-value (the inelasticity of the collision) allows first to give a new insight in the

mechanisms involved in double electron capture reactions [2] and second to test precisely the different theories which are available to day.

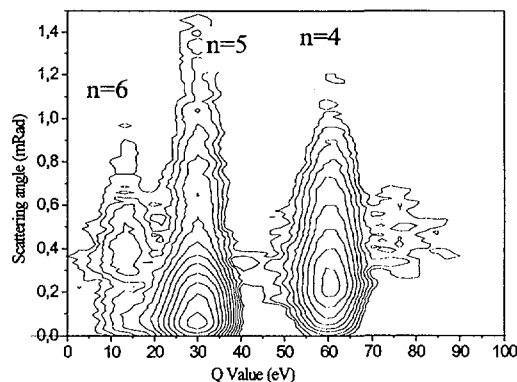


Fig: Exemple of high resolution doubly differential cross section for the Ne^{10+} - He at 150 KeV.

Since recoil ions are detected in coincidence with scattered projectiles, we are able to separate the processes leading to stabilized double electron capture from the processes leading to autoionizing double electron capture. This give access to the selective stabilisation ratio and to the Auger yields which are essential in the understanding of post collisional interactions.

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(n, l, m_l) selectivity of the single electron capture for low energy X⁸⁺(X≡Ar,Kr,O)-Li(2s) collisions

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Single electron capture is studied by photon spectroscopy for the X⁸⁺(Ar, Kr)-Li(2s) collision system between 0.1 and 5 keV/amu in the 200-600 nm wavelength range. From recorded photon spectra, production cross sections $\sigma(n\ell)$ of each $n\ell$ configuration populated by single electron capture (SEC) process are determined. For both systems, the preferentially populated levels are $n=8$ and 9. This n distribution is nearly independent of the collision energy between 0.1 and 5 keV/amu.

The ℓ distribution behavior versus the collision energy is completely different. As it is shown in figure 1, at high energy, only high ℓ configurations are mainly populated. For low energy collision, comparison with classical trajectory Monte-Carlo (CTMC) calculations on O⁸⁺(bare ion)-Li system allows the following conclusion : the effect of the core electron projectile becomes efficient and contributes to the population of the low ℓ configurations¹.

The polarisation of each observed line due to SEC is measured. Transitions between low configurations are not significantly polarised contrary to transitions between high l configurations. The figure 2 shows the polarisation degree evolution of the $7\ell-8\ell$ Ar⁸⁺-Li transition. This behavior can be explained in the following way : as the collision energy decreases, the core effect is more efficient and the rotationnal

coupling becomes an intrashell coupling yielding to a m_ℓ distribution widening and a polarisation degree diminution. At very low energy, the rotationnal coupling efficiency decreases allowing the increase of the polarisation degree².

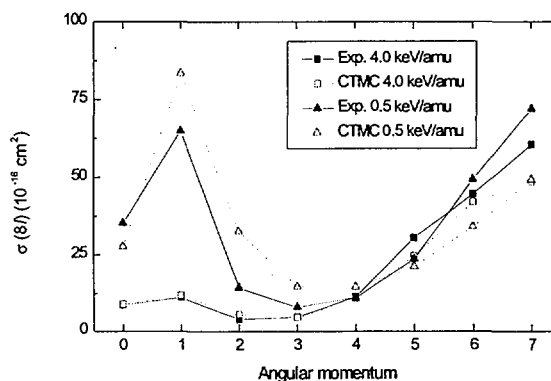


Figure 1

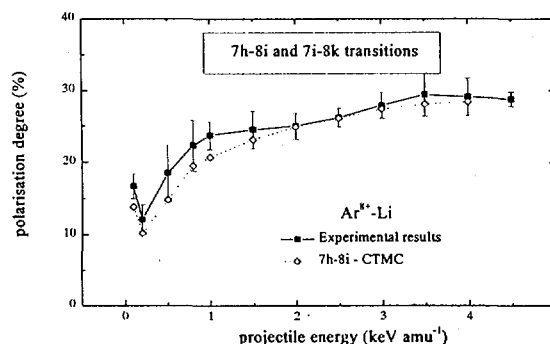


Figure 2

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² Laulhé C., Jacquet E., Cremer G., Pascale J., Boduch Ph., Rieger G., Chantepie M., Lecler D., Phys.Rev.A **55** (1997) 1088.

Fast ion-induced molecule fragmentation

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The relaxation of multi-ionized molecules has been a subject of extensive studies during last decade. The ejection of several electrons through core excitation or direct outer-shell ionization leads to fragmentation of the molecule, as soon as the electrons participating to the chemical bond are removed. The use of swift heavy ions provides a powerful tool to remove many electrons in one collision. Thus, it gives access to the study of highly charged transient molecular ions. Moreover, the characteristic time scale for the multi-electron removal by swift ions is of the order of 10^{-17} s, i.e. about 10^3 times shorter than the multiphoton ionization produced by up-to-date intense femtosecond lasers.

In this work, we have studied the fragmentation of the carbon monoxide (CO) molecule induced by a 6.7 MeV/A Xe^{4+} projectile (about 16 a.u. for the projectile velocity). We extend the previous CO fragmentation results in the strong interaction regime ($q/v_p \gg 1$, where q is the projectile charge state and v_p the projectile velocity), for which no experimental data have been yet reported. The experiment was performed on the LISE (Ligne d'Ions Super Epluchés) line at the GANIL facility. A 1/100 repetition rate has been used for the 10 MHz pulsed projectile beam. The CO target is provided by a supersonic gas jet to avoid the thermal energy spread which limits the momentum resolution. The two fragments are extracted from the collision region, perpendicularly to the ion beam, by a uniform electric field (from 130 to 410 V/cm) and detected on a micro-channel plate detector. The experimental technique is based upon a coincident time of flight measurement of the two fragments, similar to the PIPICO (Photo-Ion Photo-Ion COincidence) method usually performed in photoionization works. We measure the TOF of the first fragment and the time difference between the two ions coming from the molecular fragmentation on the same detector. Then, we use a trajectory simulation in the spectrometer to convert the time difference into total KER distributions.

We have studied the dissociation pathways of the highly charged ions up to CO^{9+} as well as branching ratios and multi-electron removal cross sections. In the case of such large impact parameter multi-ionizing collisions, the energy transferred to the nuclei of the molecule is small. In a previous ion-atom experiment performed at GANIL with He and Ar gaseous targets, we have measured, for the same projectile, that the most probable value of the recoil ion kinetic energy ranges between 1.17 meV and 9 meV for He^{1+} and He^{2+} and between 0.32 meV and 38.5 meV from Ar^{1+} up to Ar^{7+} [Jardin *et al.* 1996]. Then, the energy liberated in the dissociation process is directly reflected in the final velocities of the fragments. It is possible to determine the Kinetic Energy Release (KER) distributions from the time of flight (TOF) difference spectra. The main results can be summarized as follow :

- we have determined the KER distributions for 18 dissociation pathways from transient CO^{2+} to CO^{9+} . Note that one can deduce from these KER the CO^{q+} transient molecular excited states. The potential energy curves are well-known only for the very low charge states of the molecular ions ($Q \leq 2$) at least in the Franck-Condon zone and for the lowest excited states. A comparison of these KER is possible as a function of the interaction strength of the perturbation experienced by the target during the collision by using projectiles of various charges and velocities ($0.1 < k = q/v_p < 2.7$). The conclusion is that, if the increase of the interaction strength seems to favour high-lying components in these KER distributions, from the perturbative regime ($k < 1$) to the intermediate one ($k \approx 1$), this extension to the higher energies « saturate » in the strong interaction regime ($k > 1$). Similar behavior has been recently observed in ion-atom collision experiment, made on the GANIL SME (Sortie Moyenne Energie) line, devoted to the *projectile* excitation. The competition between the shift of the impact parameter-dependent ionization probability $P(b)$ to higher b values and the increase of the ionizing power results in a nearly constant interaction between the

projectile and the target. The results of the present work strengthen this qualitative interpretation, near from the ion-atom behavior.

- Multi-electron removal is found to represent about 40% of the ionizing events. It exhibits the high ionizing power of such heavy ion in the strong interaction regime, already pointed out in the atom ionization case. In the low molecular ion charge state cases, electron removal is highly dominated by valence electron ionization. However, for high charge states, inner-shell electron capture is estimated to be competitive compared to multiple ionization. Then, this electron capture greatly favours the multi-electron removal events and enhances the corresponding cross sections compared to the single ionization ones.

- In the excitation-ionization channel ($Xe^{4+} + CO \rightarrow CO^{++}$), only $(26.8 \pm 0.2)\%$ of the CO^{++} ion dissociates. The main fragmentation pathway is the C^+/O channel. For this one, we have directly measured the KER distribution through the determination of the full momentum vector of the C^+ fragment by Recoil Ion Momentum Spectroscopy (RIMS). This has been achieved by TOF measurement and ion impact position determination, giving access to the angular and KER distributions in coincidence. For a 410 V/cm extraction field, the momentum resolution is around 8 a.u. for the C^+ fragment. It improves the KER distribution resolution and evidences high-lying excited components produced by the excitation-ionization process (figure 1). The higher states (γ and δ on figure 1) correspond to a total energy deposited by the projectile of 42.3 eV and 51.2 eV respectively, above the double ionization threshold.

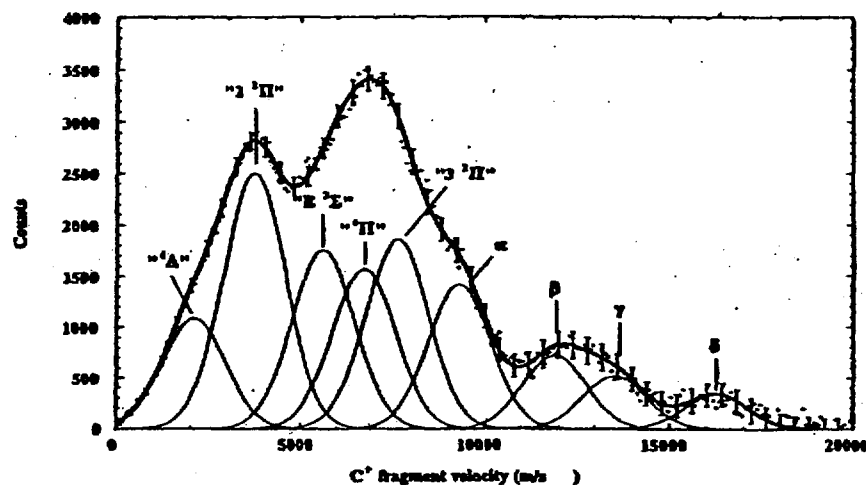


Figure 1 : C^+ momentum distribution for the $CO^{++} \rightarrow C^+ + O$ fragmentation channel.

Recently, we have implemented a multi-hit position sensitive detector which allow the full momentum vector determination of all the fragments in coincidence. Thus, in the near future, the attention will be turned to the study of the evolution of the (multi-)ionization cross section versus the angle between the internuclear axis of the diatomic molecule and the ion beam direction. Further experiments on the dissociation of the water molecule are also scheduled. The study of the radiolysis of water becomes a subject of growing interest since, from a radiobiological point of view, most of the energy deposited by ionizing radiations is absorbed by this molecule. The results are still scarce in the case of high Linear Energy Transfer radiations.

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2 - SWIFT HEAVY ION INDUCED MODIFICATION IN MATERIALS

TEMPERATURE DEPENDANCE OF DAMAGE CREATION IN BISMUTH BY SWIFT HEAVY IONS

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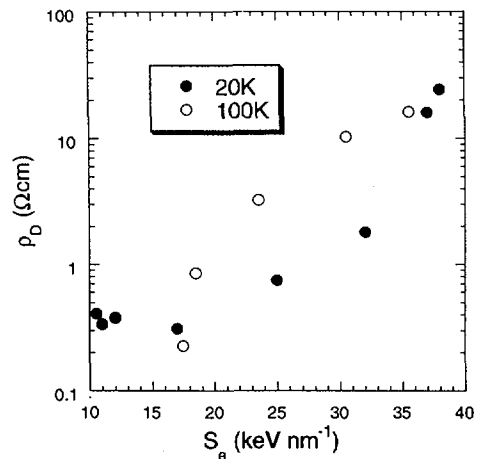
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The behavior of metallic materials [1] as well as insulators [2] under swift heavy ion irradiations has been extensively studied and correlated to the thermal spike model [3,4]. In the framework of the thermal spike model the energy deposited on the target electrons is transferred to the lattice causing a local temperature increase. A molten phase could then appear around the ion path and give place to the so-called latent track after ultrafast quenching. A first evidence of an effect of the temperature increase along the ion path is the annealing of the defects created by nuclear collisions [5] below the electronic stopping power threshold of damage creation. This annealing can be quantified by the thermal spike model [6].

In this work we add a new element in favor of the thermal spike model: the effect of the temperature of irradiation. The energy necessary to melt a material is all the lower as the initial temperature of irradiation is high. Bismuth is a good material to test this fact because of its low melting point and its sensitivity to the electronic stopping power S_e of swift heavy ions [7]. This sensitivity has been experimentally evidenced by measuring the sample resistivity ρ as a function of the ion fluence Φt (Φ is the flux and t the irradiation time) for

different ions and consequently for different values of stopping power.

In order to quantify the effect of the temperature of irradiation on the damage creation in bismuth, this material has been irradiated with 5.8 GeV of xenon and 6.5 GeV tantalum ions at 20K and 100K. 100K was chosen because at this temperature there is no annealing of defects created by the ion irradiations in the electronic stopping power regime [7]. Aluminum degraders were used to decrease the beam energy and to select several values of S_e between 17 and 40 keV nm⁻¹. In order to characterize the S_e effect we analyze the evolution of the resistivity increase versus the fluence Φt .



Then we define the following parameter $\rho_D = (1/\sigma_t)(d\rho/d\Phi t)_{\Phi t=0}$ [7] where σ_t is the damage cross section of elastic collisions. The figure shows the ρ_D values versus the electronic stopping power for the two temperatures of irradiation. The values of ρ_D are higher in the case of the irradiations performed at 100K than at 20K. The damage efficiency is therefore higher at 100K than at 20K as expected by the thermal spike model. For values less than 18 keV nm⁻¹ when only nuclear collisions are responsible of the defect creation, ρ_D is lower at 100K than at 20K due to the annealing of the Frenkel pairs at 45K [7].

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Electronic stopping power threshold of sputtering in yttrium iron garnet: comparison to the latent track appearance.

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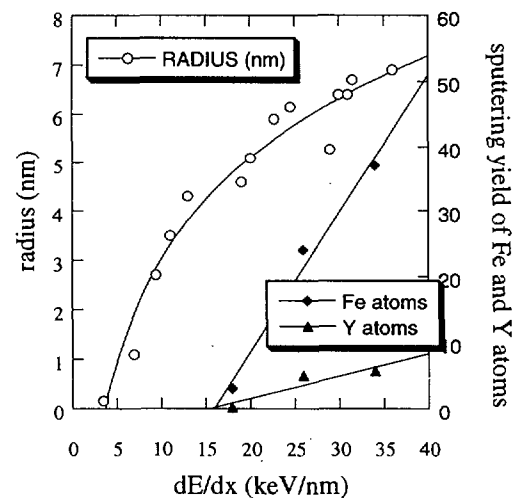
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The sputtering of yttrium garnet ($\text{Y}_3\text{Fe}_5\text{O}_{12}$) have been studied in the electronic stopping power (dE/dx) regime in order to compare the sputtering efficiency to the latent track creation [1].

Single crystal of $\text{Y}_3\text{Fe}_5\text{O}_{12}$ have been irradiated at room temperature with ^{86}Kr (energy 195 MeV, $dE/dx = 18$ keV/nm), ^{181}Ta (400 MeV, 34 keV/nm) and ^{235}U ions (150 MeV, 26 keV/nm) through an aluminum degrader placed 1mm in front of the sample. The sputter atoms are collected on this aluminum foil called the catcher.

The catcher was analyzed using Rutherford backscattering spectrometry using 1 MeV of alpha or ^{12}C beam. Using Carbon beam the sensitivity is as low as 2×10^{12} Fe per cm^2 allowing low fluence of irradiation to avoid the damage recovery linked to the track creation. Moreover with such fluences the sputtering of the deposited atoms on the catcher is negligible.

The results of the sputtered Fe and Y atoms are presented on the figure and compared to the evolution of the latent track radii versus the electronic stopping power. It should be mentioned that this electronic sputtering does not follow the stoichiometry of the garnet. By a linear extrapolation of the Fe and Y atom sputtering yield, the electronic stopping power threshold of electronic sputtering is the same for the two species and is equal to 16 ± 3 keV/nm [2].



This threshold is four times higher than the one determined for the damage creation which is 4 ± 1.5 keV/nm [3] in the same energy range of the sputtering experiments.

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Angular distribution of neutral atoms sputtered by heavy ion bombardment.

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The experiments done at the surface of the materials can improve our knowledge of the damage mechanism under high electronic excitation. Information about how the atoms are moved off in the track can be obtained from the energy and the angular distribution of the atoms ejected by the ion impact. Since most of the atoms ejected are not ionised, the most used and the simplest technique is to catch the sputtered atoms on a clean surface. In this study, we have chosen a material in which latent tracks have been measured [1] and which presents a high detection efficiency : the Uranium dioxide. The sputtered Uranium atoms are collected on a mica foil which is subsequently irradiated with thermal neutrons to fission the ^{235}U . The fission fragments create latent tracks in the mica which are revealed by chemical etching. The angular distribution of sputtered Uranium is determined from the spatial distribution of the tracks on the mica detector [2].

The angular distribution can be fitted with a \cos^n law with $n \sim 3$ which indicates a preferential emission perpendicular to the surface. The total yield is obtained by integrating over the solid angle. For $^{116}\text{Sn}^{36+}$ (4.6 MeV/A) ions, 54.4 ± 9.3 Uranium atoms are ejected per incident ion, while for $^{238}\text{U}^{55+}$ (3.5 MeV/A), this number increases up to 4800 ± 450 . This huge variation is still debated but could reflect the evolution of the track morphology (from discontinuous to continuous track). The direct observation of the surface of damaged UO_2 by near-field microscopy gives information about the origin of the atoms ejected by the ion impact.

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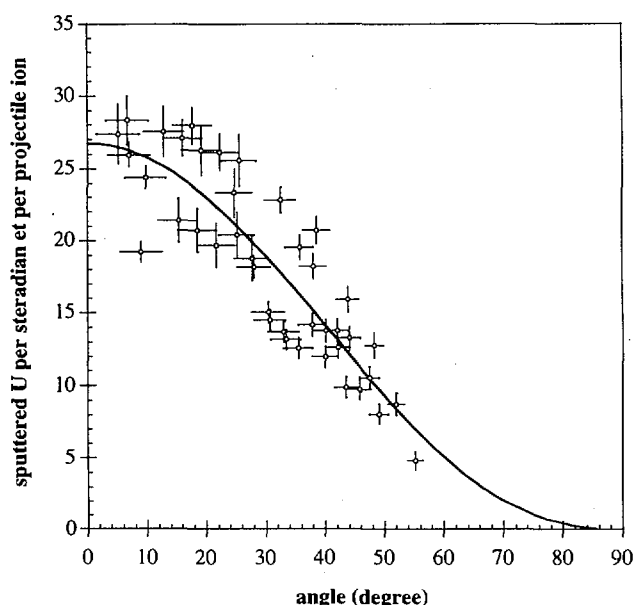


Figure : Angular distribution of Uranium atoms sputtered by the interaction of $^{116}\text{Sn}^{36+}$ (4.6 MeV/A) with an UO_2 target. The line indicates the best fit with a $\cos^n \theta$ law.

Effect of the energy density near the ion path on the track formation in mica.

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Since the first experiment done by near field microscopy [1], the efficiency of this method for the visualisation of the surface modifications induced by the swift heavy ions has been demonstrated. In mica, the evolution of the track diameter has been measured as a function of the electronic stopping power (LET) [2]. For the high-velocity ions ($E > 1$ MeV/A), above a LET threshold of about 5 keV/nm, the track diameter increases linearly with the LET (figure 1). However this curve is no longer valid for low-velocity ions ($E < 1$ MeV/A). In this case, the tracks are detectable below this threshold and, for a given LET, a low-velocity ion produces a larger track than a high velocity ion.

Thus the LET of the ions is not a sufficient parameter to characterise the induced modification. A better parameter should be the density of energy deposited near the ion path. This density of energy can be obtained from a simulation of the energy transfer to the solid [3]. Since the energy deposited near the ion path comes essentially from the low energy electrons, we have evaluated the part of the LET which corresponds to the production of these low-energy electrons : the reduced LET. The figure 2 shows that there is no more difference between high- and low-velocity ions if the track diameter is plotted as a function of this reduced LET [4].

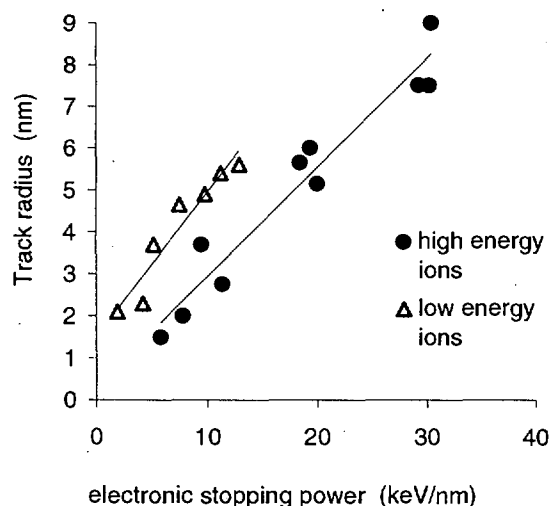


Figure 1 : Track radius measured in mica for high-energy ions (GANIL experiments) and low-energy ions (irradiations done at Bruyères le Chatel).

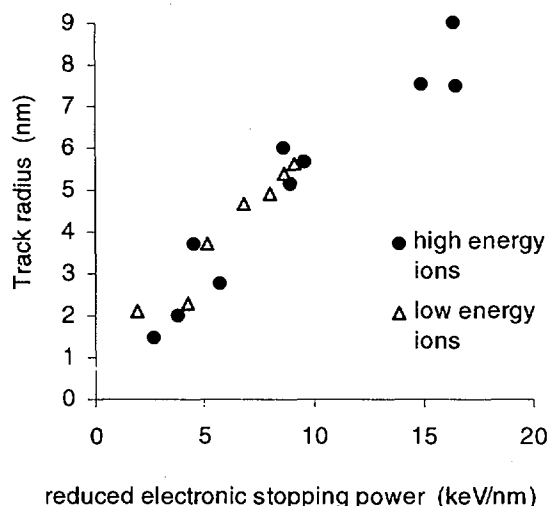


Figure 2 : Track radius plotted as a function of the electronic stopping power corresponding to the production of low-energy electrons (<200eV).

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MODIFICATIONS INDUCED BY SWIFT HEAVY ION IRRADIATIONS IN METALLIC OXIDE POWDERS (Y_2O_3 AND SnO_2)

Exp P. 373 (E. Dooryhée)

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The study of the interaction between swift heavy ions and bulk materials shows that the effects depend on the electronic stopping power S_e , resulting in track creation in S_e sensitive materials.

In the present study, we are interested in knowing whether the swift ion irradiation effects are influenced by the finite size of the sample. We choose to irradiate powders of materials which are insensitive to S_e in their bulk form.

In this content, two metallic oxide samples (powders, sintered sample or single crystal in some cases) were used : yttrium oxide (Y_2O_3) for which preliminary results were obtained by V. Chailley and tin oxide SnO_2 .

Yttrium oxide was irradiated with several ions in a large range of S_e value. The different samples exhibit different behaviors under irradiation. In some of them, the structure changes from cubic (stable in normal conditions) to monoclinic (stable under high pressure and high temperature). This transition is studied by X-ray diffraction using the CHEXPIR facility in-situ. The single crystal seems insensitive, while the sintered sample is sensitive only at high S_e value. The powder remains cubic at low S_e value, but is more and more sensitive when S_e increases. The efficiency of the transformation measured by the volumic proportion of cubic phase in the sample, is determined by Rietveld analysis which also gives the evolution of the grain size and of the stresses into the grains during irradiation.

Concerning the tin oxide, the effects of swift heavy ion are studied by transmission and high resolution electron microscopies, before and after irradiation. Thus, with increasing Pb fluences, modifications of grains which occur above a critical fluence of $2 \cdot 10^{12}$ Pb cm⁻² have been observed. The grains lose their initial shape and some nanodomains are formed presumably due to grain bursting followed by sputtering and redeposition. The smallest grain disappear after irradiation.

The results obtained on each oxide may be interpreted with the aid of the thermal spike model, if modifications are introduced to take into account the increase of pressure due to temperature.

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- TEM study of irradiation effects on tin oxide nanopowder
S. Hémon, F. Gourbilleau, C. Dufour, E. Dooryhée, E. Paumier
Nucl. Inst. Meth. B, 1997, **122**, 526-529
- Phase transformation of polycrystalline Y_2O_3 under irradiation with swift heavy ions
S. Hémon, V. Chailley, E. Dooryhée, C. Dufour, F. Gourbilleau, F. Levesque, E. Paumier
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- The thermal spike model : a possible way to describe the effects induced in matter by swift heavy ion irradiation
C. Dufour, S. Hémon, F. Gourbilleau, E. Paumier, M. Toulemonde, E. Dooryhée
Mater. Sci. Forum, 1997, **248-249**, 21-31
- Nanometric size effects on irradiation of tin oxide powder
A. Berthelot, S. Hémon, F. Gourbilleau, C. Dufour, E. Dooryhée, E. Paumier
Accepté pour publication dans Nucl. Inst. Meth. B
- Influence of the grain size : yttrium oxide irradiated with swift heavy ions
S. Hémon, C. Dufour, F. Gourbilleau, E. Paumier, E. Dooryhée, S. Begin-Collin
Accepté pour publication dans Nucl. Inst. Meth. B

Swelling of insulators under ion irradiation

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Many solids exhibit volume expansion under various types of radiation such as photons, electrons, or neutrons. Recently, swelling effects have also been observed when irradiating Al_2O_3 [1] and LiNbO_3 [2] with energetic heavy ions. In order to test if this macroscopic volume increase is a general modification induced by ions in the electronic energy loss regime, we irradiated several insulating crystals (LiF , SiO_2 quartz, and $\text{Gd}_3\text{Ga}_5\text{O}_{12}$ garnets) using a wide variety of ion species [3,4]. About 1 mm thick slabs of single-crystals with polished surfaces were irradiated at the 7 MV tandem Van de Graaff in Bruyères-le-Châtel (F, S, and Cu), at the UNILAC of the GSI (Kr, Au, and U), and at the SME beamline of the GANIL (C, Kr, Mo, Xe, Ta, and Pb). The energy varied from 0.8 to 11.4 MeV/u, corresponding to ion range in the crystals between a few and 100 micrometers.

In all crystals, we observed a significant out-of-plane swelling. Due to the fact that the ions were stopped in a thin surface layer, the free expansion of the irradiated volume is partially limited by the constraint of the undamaged substrate. As a consequence, the sample bulges outwards mainly normal to the sample surface. The quantitative analysis of the swelling was performed with a profilometer (Dektak 8000) where a diamond-tipped stylus scans over the border line between an irradiated and a virgin area. Typical scans of $\text{Gd}_3\text{Ga}_5\text{O}_{12}$ crystals irradiated with Cr ions of various fluences are shown in Fig. 1. Depending on the ion fluence, the electronic energy loss, the total ion range, and the material, the step height varied between 20 and a few hundred nanometers.

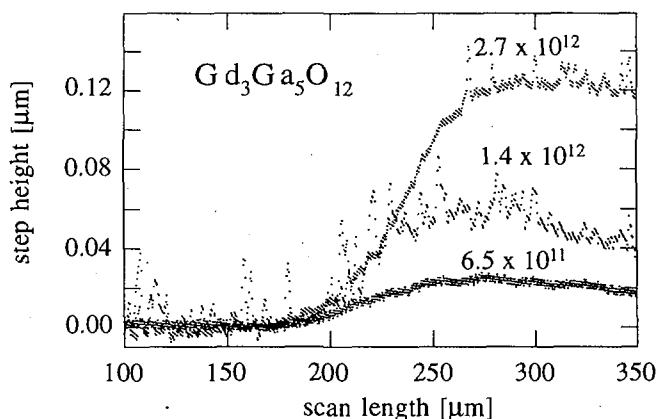


Fig. 1. Profilometer scans from the virgin (left) to the irradiated (right) area of $\text{Gd}_3\text{Ga}_5\text{O}_{12}$ crystals irradiated with Cr ions (6.2 MeV/u) of various fluences (ions/cm^2).

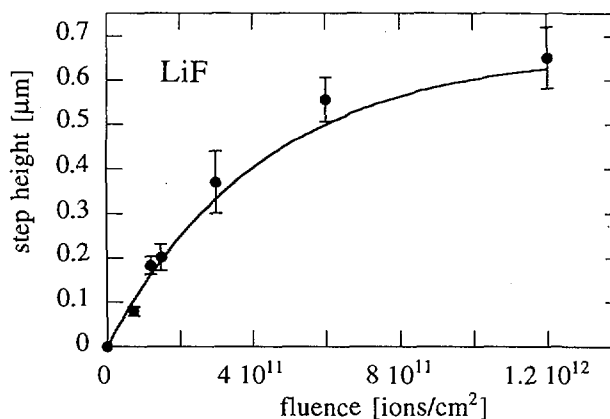


Fig. 2. Step height as a function of the fluence for LiF irradiated with Pb ions (4 MeV/u).

The characteristic evolution of the step height as a function of the ion fluence is illustrated for Pb ions in LiF in Fig. 2, where an initial linear increase, the curves approached saturation at high fluences.

In order to test the correlation between swelling and energy loss, we determined the relative contribution of each single ion per unit damage length. This was done by plotting the initial rate of swelling ($\Delta l/\Delta \phi$) divided by the projected ion range R versus the mean energy loss (Fig. 3). Fitting a linear curve to the experimental data, a threshold of 1.8 ± 0.5 and 7 ± 2 keV/nm was deduced for SiO_2 and $\text{Gd}_3\text{Ga}_5\text{O}_{12}$, respectively. Below this critical energy loss, obviously the damage along the ion path does not effect the expansion of the sample

dimension. Both values are in good agreement with the threshold for damage creation as determined from the Rutherford backscattering experiments under channelling condition (C-RBS) [5,6].

Another interesting observation concerns the increase of the swelling effect for larger ion ranges. For a quantitative analysis, the step height was normalised by the damage fraction F_d as known from C-RBS experiments. Fig. 4 clearly demonstrates that the swelling effect has a linear dependence on the track length. It also shows that the damage induced by the electronic excitation is not efficient along the total range of the incident ion. It is interesting to note that the relative dimensional change of 0.04 is the same for $Gd_3Ga_5O_{12}$, SiO_2 , and $LiNbO_3$. In oxides, this observation can be understood based on the finding that tracks consist of amorphised cylindrical zones. As a consequence of the transition from the crystalline to the amorphous phase, each individual track undergoes a volume expansion finally leading to a macroscopic out-of-plane swelling.

For materials such as LiF and other alkali-halides, the situation is different because ionic crystals can not be amorphised. Up to now, the correlation between the type of defects and volume increase is still an open question. In any case, the swelling experiments clearly demonstrated that profilometry can be applied to probe the sensitivity of a wide variety of materials.

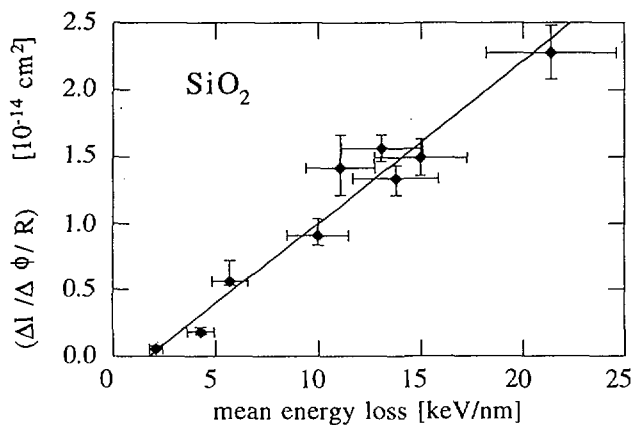


Fig. 3. The initial swelling ($\Delta I / \Delta \phi$) per ion normalised by the range R versus the mean energy loss in SiO_2 quartz.

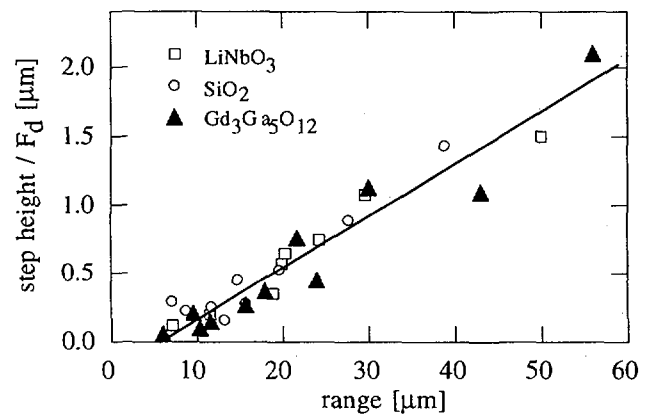


Fig. 4. Step height normalised by the damage fraction F_d as a function of the ion range for various oxides.

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Damage morphology of ion irradiated lithium fluoride

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Single-crystals of lithium fluoride were irradiated with various ion species at the GANIL and at the GSI in the energy regime between 1 and 30 MeV/u. The induced radiation damage was studied with techniques such as optical absorption spectroscopy [1], small-angle x-ray scattering (SAXS) [1], chemical etching [2] and profilometry [3], complemented by annealing experiments [3]. Clear evidence is given for a complex track structure and defect morphology.

Fig. 1 shows the number of F - and F_2 -centers as a function of the fluence of Pb ions of 4 MeV/u. From the saturation curve, it can be deduced that such simple defects are produced mainly in a large halo of several tens of nanometers around the ion trajectory. The defect creation in this zone is similar to that under conventional radiation.

New phenomena occur for heavy ions above a critical energy loss of about 10 keV/nm. Within a very small core region of 2-4 nm in diameter, a new type of damage is produced generating a characteristic anisotropic SAXS pattern. Moreover, the tracks can be preferentially attacked by a chemical etchant, resulting in the formation of pyramidal-shaped etch pits (Fig. 2). Due to very similar annealing properties, it is concluded that the etchability and the anisotropic x-ray scattering are both based on the creation of complex defect aggregates possibly small colloids, fluorine clusters and vacancy clusters. Their formation is only slightly influenced by the irradiation temperature and takes place even at 15 K where diffusion processes of primary defects are frozen [4].

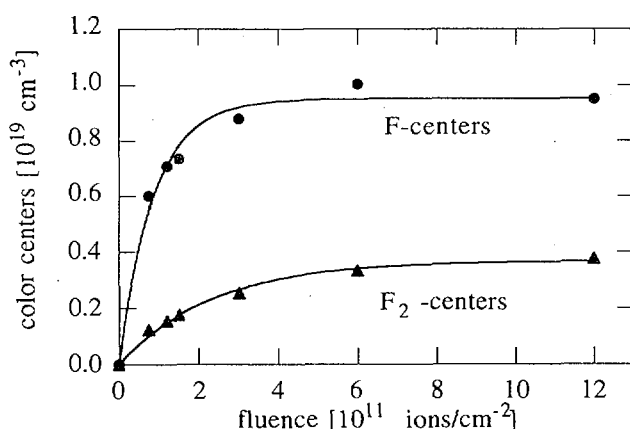


Fig. 1. The concentration of F - and of F_2 -centers as a function of the fluence of Pb ions (4 MeV/u).

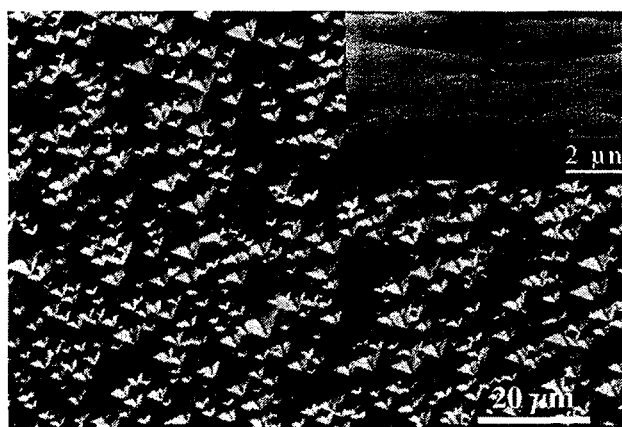


Fig. 2. Surface of an etched LiF crystal irradiated with 10^7 U-ions/cm² of 11.4 MeV/u. Each track is revealed by a pyramidal-shaped etch pit (inset).

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Structural and magnetic modifications induced by heavy ions irradiation in Fe-R-B amorphous alloys

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Owing to the topological disorder and the spin-orbit coupling, amorphous alloys with Transition Metal and Rare earth (R) elements can exhibit random magnetic anisotropy, which is of fundamental interest accounting for the variety of spin structures that may be reached. A previous Mössbauer study of melt-spun amorphous $\text{Fe}_{80-x}\text{R}_x\text{B}_{20}$ ribbons ($\text{R} = \text{Ho}, \text{Dy}, \text{Nd}$; $x \leq 16$ at.%) evidenced for a strong modification of the Fe environments in the rare earth concentration range $x^c \approx 8-9$ at.%, whatever the nature of the rare earth. Above x^c , the materials display random magnetic anisotropy, while below x^c , magnetic texture effects depending on the nature and the concentration of R are observed. The present work was undertaken with the aim to study the effect of swift ions irradiation on these properties. The modifications were investigated at room temperature by Mössbauer spectrometry and X-ray diffraction.

Amorphous $\text{Fe}_{80-x}\text{Dy}_x\text{B}_{20}$ ribbons ($x = 6, 10, 16$ at.%) were irradiated with Xe and Pb ions at fluences up to 3×10^{12} ions. cm^{-2} . For all concentrations, we observe a rotation of the iron hyperfine fields towards the ribbons plane, whatever the initial magnetic texture is. This behaviour is probably related with the positive sign of the magnetostriction constant in the ribbons. In the lower fluences range, the rotation effect is enhanced for the lower rare earth concentrations, in agreement with the higher magnetostriction constant values. From the corresponding variation of the transformed fraction as a function of the fluence, a track radius of the order of 5 nm can be estimated.

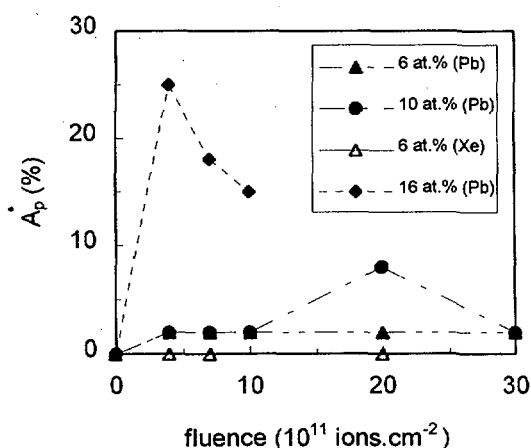


Fig.1 : Mössbauer abundance of the paramagnetic phase in $\text{Fe}_{80-x}\text{Dy}_x\text{B}_{20}$ ribbons irradiated with Pb and Xe ions.

We also observe the appearance of a paramagnetic component on irradiation. When the R concentration is increased, its formation occurs at lower fluences, and its fraction is enhanced (Fig.1). Its presence is also favoured in the case of Pb ions. From the Mössbauer and X-ray diffraction measurements, it would be attributed to R-enriched zones. At higher fluences, the paramagnetic phase tends to vanish, as seen for higher R concentrations (Fig.1).

This behaviour suggests a two-step transformation with first, irradiation-induced segregation phenomena in the amorphous state and second, a mixing that reduces the zones previously enriched in rare earth. Further structural investigation of this component is in progress.

Ion irradiation effects on bcc-Fe/Tb multilayers

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Fe/Tb multilayers are of great interest because of their promising application in magneto-optical recording media. The aim of this work was to study the influence of swift ion irradiation on the structural and magnetic properties of Fe/Tb multilayers in order to improve the perpendicular magnetic anisotropy needed for high-density data storage.

Fe/Tb multilayers with crystallized Fe layers were irradiated with Ar, Kr, Xe, Pb and U ions at various fluences[1]. Damaging processes, investigated by ⁵⁷Fe Mössbauer spectrometry at room temperature, give evidence for three thresholds, one for the damage formation ($5 \text{ keV/nm} < T_0 < 15 \text{ keV/nm}$), one for Fe-Tb mixing threshold ($T_1 \sim 25 \text{ keV/nm}$) and one relative to the creation of defects in the bcc-Fe layers ($T_2 \sim 45 \text{ keV/nm}$). If the electronic stopping power $(dE/dx)_e$ value of the ions is higher than T_0 but less than T_1 , only a demixing of Fe and Tb atoms occurs at the interfaces, producing both a thickening of the pure bcc-Fe layer and a sharpening of the interfaces whatever the ion fluence is. Between T_1 and T_2 , the Fe-Tb demixing is still observed at the lowest fluences, but then the mixing of Fe and Tb layers destroys progressively the layered structure. At high-ion fluences, the samples exhibit the magnetic properties of the corresponding amorphous Fe-Tb alloys. When the energy deposited by the ions exceeds the T_2 value, a third phenomenon appears in addition to the two previous ones: the initial bcc Fe layers are transformed into "pure" disordered Fe layers.

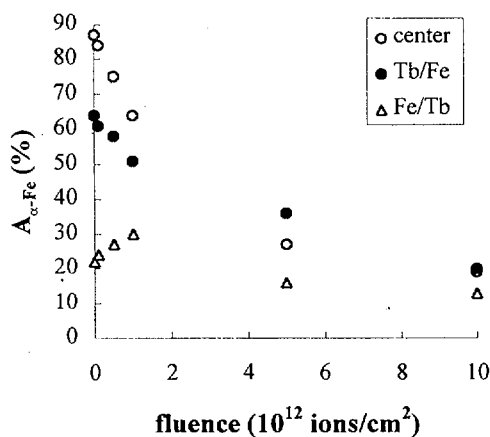


Fig.1: Relative fraction of Fe atoms which are in the α -phase compared to all Fe atoms for (Fe 3.8nm / Tb 1.9nm)₂₀ multilayer irradiated with 811 MeV U ions.

In order to study more precisely the previous phenomena, probe multilayers have been made by depositing 0.5 nm of pure ⁵⁷Fe selectively either at the sharp Tb/Fe interface, or at the diffuse Fe/Tb interface, or in the center of Fe layers [2].

Investigations on Sn and U-ion irradiated probe multilayers by ⁵⁷Fe Mössbauer Spectrometry show that the demixing effect is localized exclusively at the diffuse Fe/Tb interface. At the flat Tb/Fe interface, only the mixing is observed (see figure 1).

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SWIFT HEAVY ION EFFECTS IN POLYMERS

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Since 1986, our team in Saclay is interested in radiation effects in polymers. The pioneer work on the swift heavy ion (SHI) effects in polymers was performed in collaboration with the CIRIL, Caen, France. These former studies focused mainly on the polymer surface evolution under ionising radiation. Since then, our interest grew in the field of chemical modifications induced by SHI in the bulk of the polymer. Modification of polymer properties was also investigated^{1,2}.

When a polymer is irradiated with ionising radiations such as electrons or γ -rays, modifications occurs which consists in crosslinking, unsaturations (isolated and conjugated), chain scissions, gas evolution, amorphisation and radical formation. These latter can have different life-times. The transient species can be observed at low temperature while the stable ones exist at room temperature and can be detected several days or months later. Among such radicals, those created in poly(vinylidene fluoride) (PVDF) are especially stable and have life-time of several years even if samples are kept at room temperature. Very few publications deal with radicals induced in polymers by SHI, and none of them offers a clear characterisation of the species observed, though these species are necessarily involved in the formation of the other defects. The knowledge of radicals is crucial for the understanding of the formation mechanism of the other defects. In addition, radicals confer to the polymer a chemical reactivity responsible for post-irradiation processes and allowing grafting of monomers.

1) The study of radicals by electron spin resonance (ESR)

In earlier studies³, it was found that some defects such as alkynes groups are created only when polymers are irradiated with high electronic stopping power $((dE/dx)_e)$ radiations such as SHI are. Similarly, it was found that in PVDF and in addition to the usual alkyl and peroxy radicals, radicals specific of the SHI/PVDF interaction exist⁴. This latter radical shows an isotropic ESR signal and no hyperfine structure is resolved. The gyromagnetic factor is close to that of the free electron. Its shape is close to a Lorentzian and its line-width is about 0.5 mT. The intensity of the ESR signal which measures the electronic contribution of the magnetic susceptibility follows a Curie law which indicates that these centres are isolated and allows the concentration of the paramagnetic species to be determined. The absence of hyperfine structure indicates that the radical is localised in a highly crosslinked carbon structure. Indeed the radical resembles those formed in pyrolysed polymers. Therefore this radical is attributed to a dangling bond localised in a carbon cluster as observed in amorphous carbon. It can be observed at very low absorbed doses when the polymer is not carbonised. Crosslinking occurs in PVDF. Our solubility results show that the presence of an insoluble fraction correlates with the observation of the dangling bond⁵. Irradiations with various ions ranging from O to Sn from the medium energy line facility in order to study the effect of $(dE/dx)_e$ on the formation of the dangling bond have been performed. Analysis of the results is in progress. Though the dangling bond is now spectroscopically well characterised, some questions still remain : Could it be formed in other polymers than PVDF ? What is its formation mechanism, direct creation in the track core or is there an effect of the overlapping of tracks ? Is the formation of such centres an indication of pyrolytic effects in the swift heavy ion - polymer interaction ?

2) Radiation grafting

Once radicals are generated in the polymer bulk, grafting of monomers able to polymerise is possible. The grafting of polystyrene (PS) occurs in the latent tracks and the anisotropy of the SHI/polymer interaction is maintained⁶. When the grafting yield increases, the surface is progressively covered until a homogeneous layer is obtained. Analysis of the macromolecular weight distribution of the grafted chains was performed⁷. Parameters such as the absorbed dose, the $(dE/dx)_e$, the grafting time and the monomer concentration are varied. Very long PS chains (number average molecular weight of 1600000) are formed in the very beginning of grafting (30 min). At very high doses, interpretation of results are complicated by the presence of crosslinking: Only the soluble fraction can be analyzed by steric exclusion chromatography while it is observed that PS is embedded in the insoluble fraction and thus not analysed. The surface structure of the grafted polymer, analysed using X-ray photoelectron spectroscopy, was also studied as a function of $(dE/dx)_e$ ⁸. Several ions were used (O, Ar, Kr, Sn from the medium energy line facility) covering the $(dE/dx)_e$ -range of 2 to 60 MeV.cm².mg⁻¹. Radiation grafting was also performed using 8 MeV electrons in order to compare the different surface structures obtained. The grafting yields used for this study are in all cases small so that the surface is only partially covered. When irradiation conditions are such that a single latent track regime is obtained, the heterogeneity of grafting is large. When overlapping of latent tracks occurs, the homogeneity of the grafted domains becomes comparable to that of the electron grafting. When $(dE/dx)_e$ increases, the quantity of grafted PS per ion track increases. As the number of radicals per ion track increases when $(dE/dx)_e$ increases, the length of the grafted chains should become smaller as $(dE/dx)_e$ grows. This is what was observed in our preliminary experiments⁷.

The structure of SHI PS grafted films is beginning to be well understood. Now, modifying the polymer substrate or changing the PS monomer which terminates by recombination for a monomer terminating by disproportionation can lead to other structures. These studies have been initiated. Another interesting point is to understand the grafting mechanism by identifying the nature of the initiating radicals and the nature of the chemical bond existing between the polymer substrate and the grafted chain. This work is in progress.

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Cross-linking induced by high density of ionisation in polystyrene.

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The high density of ionisation produced in the wake of a high-energy ion is responsible in polymers for a significant increase of the chain scission associated with unsaturated end groups and for the creation of alkyne and allene end groups which are never produced during irradiation with low ionising particles [1,2]. Under these conditions, the creation of new bonds between adjacent chains has been less studied. The difficulty comes from that the cross-links are not induced randomly as under electron or gamma irradiation: the probability to produce several events close to each other is high. Thus under swift heavy ion irradiation, the production of large molecular masses directly in the path of a single ion is favoured [3]. The figure 1 presents the results obtained by steric exclusion chromatography for the cross-linking of polystyrene under Carbon

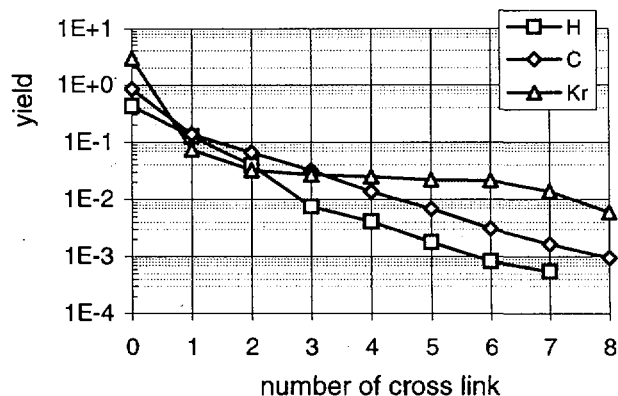


Figure 2: partial yields (100 eV^{-1}) for cross-link in polystyrene irradiated with $2.5 \text{ MeV } ^1\text{H}$, $118 \text{ MeV } ^{13}\text{C}$ and $756 \text{ MeV } ^{84}\text{Kr}$ (0 corresponds to the destruction yield).

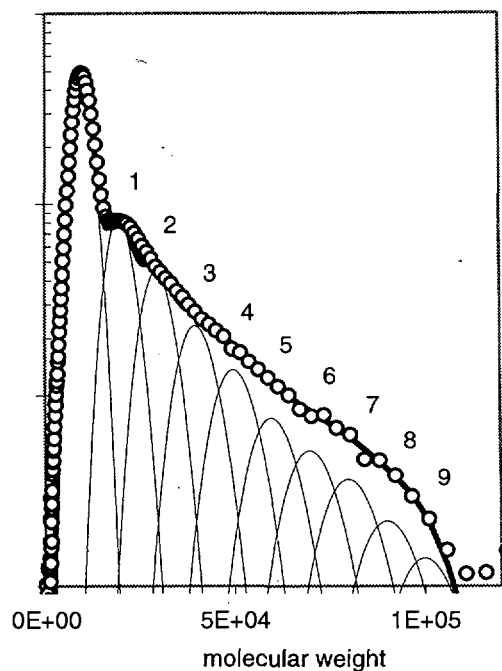


Figure 1: Molecular weight distribution of polystyrene irradiated with ^{13}C at a dose of 0.5 MGy . The numbers indicate the number of cross-links.

irradiation. From the evolution of these molecular weight distributions, we can extract the yield to produce n cross-links per chain (figure 2). The efficiency to the production of large macromolecule increases with the LET. Moreover, the destruction yield of the initial macromolecules increases also with the LET of the ion from 0.4 for Proton to 3 for Krypton.

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Ion induced alkyne formation in polymers

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Although tracks of energetic ions in polymers have been studied for many years, the characterisation of the defects in the ion track is far from being complete. In order to investigate the chemical modifications, a detailed study was performed by Fourier-transform infrared spectroscopy (FTIR). Various commercial polymer films of different aliphatic and aromatic moiety (12 μm polyimide (PI), 16 μm polycarbonate (PC), 12 μm polyethyleneterephthalate (PET), and 24 μm polysulphone (PSU)) were irradiated under vacuum and in oxygen atmosphere with Kr ions (8.6 MeV/u) at the SME beamline of the GANIL. During beam stops, the irradiated samples were transferred from the irradiation chamber to the infrared spectrometer without exposing them to air. The degradation products were found to be very similar to those under classical irradiation, e.g., alkenes, carboxylic acids, alcohols, and CO_2 [1]. As a unique process induced by the energetic ions, the formation of alkynes was observed. New absorption bands appeared which can be assigned to the characteristic C–H stretching mode of the alkyne end group ($-\text{C}\equiv\text{C}-\text{H}$) at 3300 cm^{-1} and the $\text{C}\equiv\text{C}$ stretching vibration at 2100 cm^{-1} , respectively [2] (Fig. 1). Both peaks increase as a function of the ion fluence. At very high doses, the absorption of these bands saturated due to overlapping of the tracks of single ions (Fig. 2). From this evolution, the track radius at which the created alkyne zones start to overlap was determined to be about 3 nm.

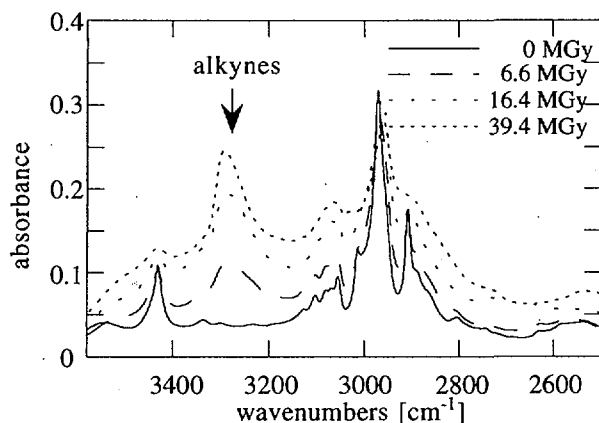


Fig. 1. FTIR spectra of PET irradiated with Kr ions (8.6 MeV/u) at various doses.

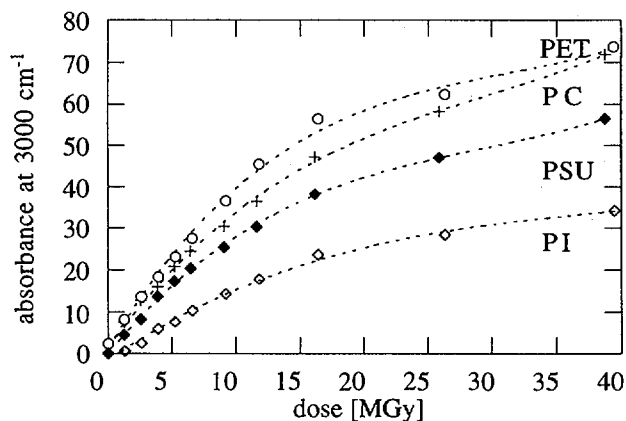


Fig. 2. Absorption of the 3300 cm^{-1} band typical for alkyne groups as a function of the ion dose for various polymers.

Complementary experiments by mass spectroscopy showed that during irradiation one of the main outgassing product is acetylene. The production of alkynes and acetylene occurs in aromatic as well as in aliphatic [3] polymers and seems to play a crucial role during the track formation. Since the creation of triple bonds requires a remarkable reorganisation of molecular bonds, it is assumed that the process is strongly related to multiple excitation and ionisation events on an extremely short space and time scale. Another interesting aspect is the similarity of the radiation products to those found in pyrolytic processes. Moreover, it is known from the cracking process that above 1230°C acetylene exhibits the highest stability compared to other hydrocarbons indicating that during track formation possibly high temperatures are involved.

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« Polymer-like » amorphous deuterated carbon films irradiated by swift heavy ions :
damage and hydrogen pumping.

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Mixed hydrogenated and deuterated « polymer-like » amorphous carbon films have been irradiated in the MeV/amu energy range with electronic stopping power varying between 1 keV nm^{-1} and 13 keV nm^{-1} [1]. These films contains 15% of hydrogen and 50% of deuterium as compared to the number of carbon atoms. Carbon (C), hydrogen (H) and deuterium (D) contents were determined by Rutherford Backscattering spectrometry (RBS) and Elastic Recoil Detection Analysis (ERDA). The figure 1 gives the evolution of the ratio (D/C) and (H/C) versus the fluence.

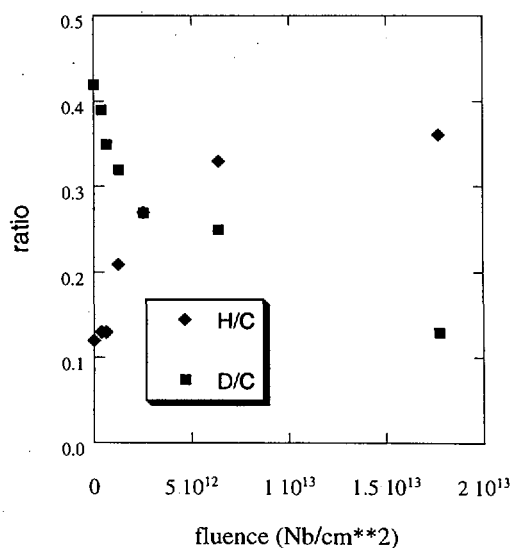


Figure 1

The main effect is the decrease of the deuterium content as compared to the number of carbon atoms versus the fluence. The second observation is the increase of the hydrogen content versus the fluence. Assuming an exponential law to fit the data [1], one can extract a deuterium effusion cross section and an hydrogen absorption cross section which are equal within the experimental errors.

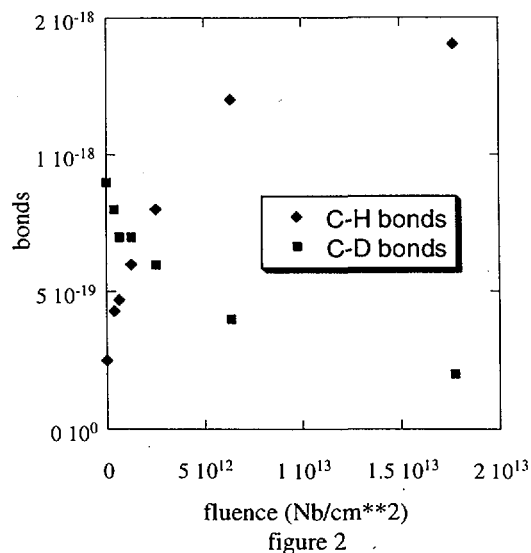


figure 2

The evolution of C-D and C-H bonds (figure 2) was determined by infrared absorption measurements. As previously observed, the main effect is also the decrease of the C-D bonds and the increase of the C-H bonds. Such an

increase appears only after one month and is stabilised only after five months. Cross sections of C-D bonds breaking and C-H bonds building can be also extracted using an exponential law and they are also equal within the experimental errors.

Moreover the cross sections extracted by the two physical characterisations (ion beam analysis and infra-red absorption) are equal leading to a latent track radius determination which is independent of the physical characterisations. The evolution of the latent tracks radius versus the electronic stopping power is presented in figure 3.

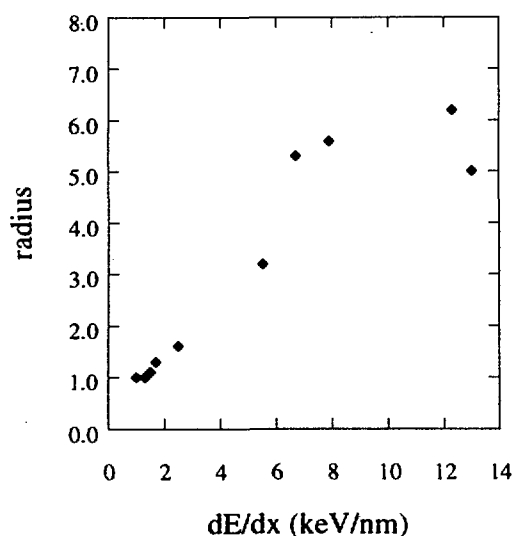


Figure 3

Hence the following interpretation is proposed: during irradiation hydrogen and deuterium atoms are ejected from the latent tracks and afterwards are replaced by hydrogen coming from ambient air and diffuse inside the irradiated material along the latent tracks.

The temperature of bond breaking by irradiation in polymers was determined

by Lewis and Lee [2]. Assuming this temperature for the « polymer-like » amorphous carbon the thermal spike model applied in the electronic stopping power (dE/dx) regime is able to predict the evolution of the latent track radii versus dE/dx [3].

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3 - RADIATION CHEMISTRY AND RADIOBIOLOGY

DIRECT TIME-RESOLVED MEASUREMENT OF RADICAL SPECIES FORMED IN WATER BY HEAVY IONS IRRADIATION

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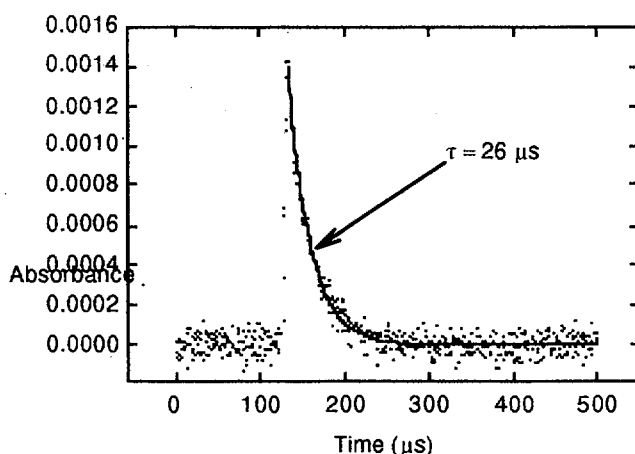
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Time-resolved absorption spectroscopy has been used to detect radical species in liquid water irradiated by swift heavy ions. These experiments have been performed at the GANIL cyclotron (Caen-France) with $^{12}\text{C}^{6+}$ (75 MeV/A), $^{36}\text{S}^{16+}$ (77 MeV/A) and $^{40}\text{Ar}^{18+}$ (70 MeV/A) particles whose the Linear Energy Transfer ($\text{LET} = -(dE/dx)_{\text{elec}}$) is respectively two and three orders of magnitude greater than electron or gamma rays. The chemistry in water is thus considerably modified at the first moments after the ionisation. In particular the radiolytic yields of the radicals like hydrated electron decrease when the LET is increasing. The temporal structure of the beam is used to perform time-resolved spectroscopy of the transient radicals formed by water radiolysis within the microsecond time scale. It is possible to show the inhomogeneous chemistry around the ion tracks and to compare these results with the Monte Carlo simulations.

Keywords : LET, heavy ions, pulse radiolysis, water radiolysis, superoxide anion, hydrated electron



This figure presents the absorbance of hydrated electron generated by 5 μs pulses of C^{6+} of 75 MeV/A of energy in pure deaerated liquid water. This curve is obtained by averaging 1000 signals.

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RADIATION YIELDS OF THE FREE RADICALS FORMED BY HEAVY IONS WATER RADIOLYSIS

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The radiolysis of liquid water by heavy ions of high LET (Linear Energy Transfer expressed in keV/μm) is characterised by the production of O₂⁻ (HO₂) free radicals, even in the absence of dioxygen, whereas in the case of ionising radiations of low LET (⁶⁰Co γ-rays), these free radicals are formed in too weak quantities to be measured. Moreover, the production of the other usual free radicals (OH, e⁻_{aq}, H) is considerably decreased, whereas the formation of the molecular products (H₂O₂, H₂) is enhanced because of the free radicals combination reactions which are favoured in the heavy ions tracks. The G-values (radiation yields expressed in mol. per Joule) of the free radicals depend not only of the LET but also, for a given LET, of the nature and of the rate of the ionising particles. In the literature, the majority of the G-values (see for example [1,2]) have been determined as a function of the *mean* LET (heavy ions being stopped in water). In our case, the experimental conditions of the GANIL allowed to measure the G-values as a function of a *really constant* LET (heavy ions cross the irradiation cell without losing energy).

Experimental data on the radiolytic yields are essential for understanding the mechanisms of formation of the free radical species. For a LET of 250 keV/μm (Ar¹⁸⁺, 95 MeV/A, dose rate 10 Gy/s, doses from 0 to 1000 Gy), we have determined the G-values for e⁻_{aq} and O₂⁻ in aqueous solutions containing tetranitromethane, C(NO₂)₄, this compound being known for its scavenging capacity of the reducing species generated by the radiolysis of water [3]. Another LET-value of 127 keV/μm (Ne¹⁰⁺, 60.3 MeV/A) has recently been investigated and this latter experiment has been performed with a new analyzing device, the spectrophotometer being in line (CIRIL, Equipe de Radiolyse du SCM CEA Saclay). The G-values deduced from these experimental data are interpreted according to the usual LET effect and hypothetical mechanisms of formation of superoxide free radicals in heavy ions tracks. The radiobiological consequences of the selective production of O₂⁻ (HO₂) free radicals are discussed.

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DNA damage induced in plasmid DNA by heavy ions and mutagenic consequences.

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Experiments numbers : P374, P397, P464.

The objective of the project is to study the genotoxic effect of high LET radiation in comparison to low LET γ radiation. The first step of the project has consisted in irradiating naked plasmid DNA with heavy ions, in solution or in dry state under vacuum or in the presence of air, exploring various LET. The induction of single and double strand breaks (SSB and DSB), as well as base damage, have been examined. These experiments aim at understanding the interaction of particles with genetic material, and to shed light in the mechanism of formation of DNA damage by ionizing radiation. In living cells, DNA lesions are either removed by various DNA repair pathways, or processed into genetic changes (mutations). The next steps of the project will consist in studying the repair of the irradiated plasmid using cell free extracts, and in monitoring the mutations produced in the irradiated plasmid DNA after introduction into mammalian cells.

pBS plasmid DNA (2961bp) has been irradiated in dry state with ^{12}C (12.4 MeV/a, LET 127 keV/ μm), ^{36}S (10.1 & 3.5 MeV/a, LET 1010 & 1650 keV/ μm) and ^{125}Te (2.63 MeV/a, LET 7830 keV/ μm), and with γ rays from ^{137}Cs source. We show that at high LET (> 1000 keV/ μm), the induction of strand breaks reaches a plateau as detected by electrophoresis, whereas it is higher for irradiation with C ion at low TEL. The ratio of SSB to DSB is 3-4 for irradiation with S or Te, 6 for C. Furthermore, for C irradiation, an increase of strand breaks is observed in the presence of air as compared to irradiation under vacuum, whereas such an oxygen effect is barely detectable with S irradiation. All these observation may be explained by a greater extent of recombination of radicals in the track at high LET. It is also in favor of increasing complexity of damage with increasing LET. Indeed, using electron microscopy, we were able to detect fragments of DNA (a main population centered around 500bp) which could not be revealed by electrophoresis. According to our preliminary data, it seems that the magnitude of fragmentation is enhanced with dose and LET.

pBS plasmid DNA has also been irradiated in solution, at various concentrations, with ^{36}S (76.2 & 66.6 MeV/a, LET 224 & 429 keV/ μm) and with γ rays. At similar doses, this last radiation produces more SSB than heavy ions, but the same amount of DSB. The ratio of SSB to DSB is 25 for γ rays and 8 for ^{36}S . For both types of radiation the induction of SSB decreases with increasing concentration. Both radiations produce base damage (revealed by DNA repair enzymes) to the same extent as SSB. However, when DNA is irradiated in a dry state, base lesions are still present after γ rays, whereas they are not detectable after S irradiation.

All the data are in favor of a complexity of the damage produced by heavy ions.

SAGE E., ROUSSET S., PERDIZ D., MARTIN C. and BALANZAT E. Détection de lésions de l'ADN induites par les radiations ionisantes de faible et fort TEL. *J. Chimie Phys.*, **94**, 331-336 (1997).

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4 - PHYSICS AND CHEMISTRY WITH TRACKS

SWIFT HEAVY ION RADIATION GRAFTING OF POLYMERS / OBTENTION OF HAEMOCOMPATIBLE SURFACES.

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Since 1980, numerous studies have been undertaken in the field of vascular prostheses, but no solution has been found to prevent the formation of a blood clot in small diameter ones (internal diameter < 5 mm). Numerous ways of those biomaterials surfaces treatment have been developed, one of which consists in producing « heparin-like » surfaces. This synthesis has been adjusted by Jozefonvicz et al. (1), whose protocol uses polystyrene (PS) chemically modified with the active groups of the heparin, a powerful blood anti-clotting substance. Unfortunately, PS does not exhibit the suitable mechanical properties for vascular implants and its ageing under blood stress is not good enough. This is why our group in Saclay has chosen a different approach based on radiation grafting using swift heavy ions. They are able to induce reactive sites in a polymer at very low doses, without modifying its chemical and mechanical properties. We adapted this synthesis to two fluoropolymer films, poly(vinylidene difluoride) (PVDF) and poly(vinylidene difluoride/hexafluoropropylene) (P(VDF/HFP)), styrene radiografted. P(VDF/HFP) has also been used as tubing (500 μ m thick and 4 mm internal diameter) in order to get closer to the vascular prostheses design shape. These fluoropolymers have been chosen for their mechanical and chemical properties as well as for their ionising radiation resistance. The additional HFP group present in the PVDF copolymer, increases its plasticity and confers better mechanical properties on our application.

The synthesis includes three steps: the first step corresponds to the initiating radicals formation, necessary to the polystyrene grafting. In order to irradiate polymers foils, different ions from the Medium Energy Line facility (SME) of GANIL accelerator have been used under an oxygen atmosphere: ⁵⁰Sn (2.99 MeV/a), ¹⁸Ar (5.63 MeV/a), ³⁶Kr (6.82 MeV/a), ⁸O (10.05 MeV/a), ³⁶Ar (10.83 MeV/a) and ¹⁸O (8.26 MeV/a). Stacks of 25 μ m thickness foils are taped on an aluminium frame and scanned vertically in front of the beam in order to obtain 4x25 cm² irradiated surfaces.

The second step of the biomaterial synthesis corresponds to the styrene monomer grafting by the indirect method (2). The sample is immersed in a styrene filled test tube, which is subsequently desaturated under a nitrogen flow, sealed and then put in a 60°C thermostated bath for a given time in order to study the grafting kinetic. The grafted sample is afterwards extracted with a Soxhlet apparatus to get rid off the homopolymer formed.

The last step consists in three successive reactions that are the chlorosulfonation, the sulfonamidation and the hydrolysis and which allow to add groups as COOH and SO₂NH to the radiografted styrene, necessary to confer the material « heparin-like » properties (3,4).

The High Energy Line facility is required to irradiate tubing because of their thickness. Irradiations were performed with ³⁶Ar (84.19 MeV/a) under an oxygen atmosphere. For the swift heavy ion irradiations, two systems have been built, one for a static tubing irradiation and the other, motor equipped, allowing the rotational movement of the tube

on its axis. In the first assembly, 4 tubes, 15 cm length, can be mounted on a frame scanned up and down perpendicularly to the ion beam; this system increases the irradiation capacity as the time necessary to get a dose of 100 kGy is relatively long and as the number of samples needed by the biological tests is very important. The second assembly has been built in order to get a more uniform tubing irradiation. The tubing are mounted on a rotating rod, fixed on the frame which scans vertically in front of the beam. As the irradiation time is much higher in this case than in the former system, only small quantities have been irradiated, the aim being the comparison of grafting yields for both systems. In the first case, the ions go through a thickness varying from 1 mm to 3.1 mm whereas in the second one, the beam is always radial to the tubing and goes through the same 500 μ m thickness.

The structure of the grafted tubing is presently in study. The functionalisation is feasible.

The biological tests are done in Bordeaux on the different steps of the films synthesis and show that the functionalisation increases the haemocompatibility properties of the material (5).

Testing of the functionalised tubing is a very important step of this research project firstly because the shape of the tubes itself which is closer to the application and secondly because some biological tests can only be done on tubing, such as those made under dynamic blood flow.

Recent tests have shown that such synthesised materials are not cytotoxic. These positive results are encouraging. The next step should be the study of P(VDF/HFP) as waved or knitted tubing.

Acknowledgements

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Simulation des dommages de fission dans les matériaux envisagés pour la transmutation des actinides mineurs

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1- Cadre d'étude

Différents matériaux utilisables comme matrice inerte de dilution ont été présélectionnés pour la transmutation des actinides mineurs en réacteur sur la base des propriétés thermophysiques au moins comparables à celles de l'UO₂ (conductivité thermique, point de fusion, et propriétés mécaniques), et sur la base de la compatibilité chimique. Parmi les critères de sélection, l'endommagement sous irradiation constitue un aspect essentiel (modifications structurales et changements des propriétés thermophysiques) mais celui-ci demeure difficile à étudier expérimentalement. Afin de caractériser l'endommagement par les fissions en réacteur, certains de ces matériaux ont été irradiés au GANIL pour simuler les dommages dus aux produits de fission.

2- Irradiations

Deux séries de matériaux ont été irradiées aux ions lourds ⁸⁶Kr et ¹⁰⁶Cd afin de simuler les effets de l'irradiation des matrices inertes en réacteur. Les deux irradiations dénommées „Matinion“ ont été réalisées sous vide, à température ambiante, sur le banc IRASME de la Sortie Moyenne Energie du GANIL. Elles ont permis d'atteindre des fluences de $4 \cdot 10^{13}$ ions/cm² pour des énergies de projectiles comprises entre 1 et 10 MeV par nucléon.

Les échantillons sous forme de disques de 5 ou 9mm de diamètre et de 100µm à 3mm d'épaisseur ont été fabriqués et caractérisés dans nos laboratoires. Les caractéristiques de quelques échantillons irradiés sont présentées dans le tableau 1.

Tableau 1 - Caractéristiques des échantillons irradiés

Matériau	Fabrication			Epaisseur		Ion		Fluence, ions/cm ²	
	CEA1	ITU	CEA2	lamé 100µm	>1mm	Kr	Cd	10 ¹¹	4.10 ¹³
MgO	x		x	x	x	x	x	x	x
MgAl ₂ O ₄	x	x	x	x	x				x
CePO ₄		x			x	x		x	x
ZrSiO ₄		x			x	x	x	x	x
CeO ₂	x	x	x	x	x	x	x	x	x
Y ₂ O ₃	x		x	x	x	x	x	x	x
YAG	x		x	x	x	x	x	x	x

3 - Etudes des échantillons irradiés

Les différents mécanismes produisant les dommages dans les matériaux lors de l'irradiation ionique (ionisation et cascade de déplacements) permettent de simuler tous les effets intervenant lors des irradiations en réacteur mais à différents niveaux : effets des produits de fission et de transmutation, effets des neutrons, et effets des rayonnements. Toutefois deux paramètres doivent être systématiquement quantifiés pour pouvoir exploiter correctement les résultats de la simulation : la fluence de l'irradiation et les dimensions des différentes zones irradiées des échantillons. Les fluences maximales de $4 \cdot 10^{13}$ ions/cm² avec Cd atteignent dans Matinon produisent des effets équivalents à ceux obtenus lors d'une irradiation aux neutrons à environ 10^{18} n/cm² lorsque l'on considère uniquement les cascades de déplacements. Comparativement aux conditions réelles envisagées pour la transmutation des actinides, ces fluences restent faibles et ne permettent d'étudier que le début de l'endommagement des cibles en réacteur. De plus les dimensions des zones endommagées par les ions sont très petites par rapport aux volumes atteints par les neutrons (généralement moins de 80µm pour l'ensemble et quelques µm pour la zone des cascades). Il reste que l'irradiation aux ions est une excellente simulation de l'irradiation par les produits de fission qui de loin produit le plus de dommages dans les matériaux.

Les échantillons irradiés ont été étudiés par microscopie optique et MEB. Beaucoup d'échantillons ont perdus leur intégrité après irradiation aux fluences élevées : fissures et clivage. Les plus dégradés sont CePO₄, ZrSiO₄, et YAG. Seuls les échantillons de MgO ont tous gardé leur intégrité. Le comportement différent observé pour des échantillons de MgAl₂O₄ originaires de fabrications différentes montre l'importance de ce dernier paramètre sur les effets d'irradiation.

Les zones irradiées présentent une coloration étudiée par spectrophotométrie sur les lames minces. Toutefois le doute n'est pas encore levé sur l'origine de cette coloration : formation de centres F ou excitation des impuretés ?

Nous n'avons pas mesuré ni observé de gonflement pour les matériaux ayant conservé leur intégrité (profilométrie et MEB). Ces mesures n'ont toutefois pas été possibles pour les matériaux les plus dégradés.

L'étude par diffraction des rayons X a été effectuée parallèlement sur la face irradiée et sur la face non irradiée des disques échantillons. Celle-ci montre en particulier une légère variation du paramètre cristallin pour MgO et MgAl₂O₄, et une déformation des pics de diffraction correspondant aux plans riches en Al.

Concernant le phosphate de cérium, des propriétés thermiques médiocres ainsi que le piètre comportement sous irradiation par des ions lourds énergétiques a conduit à éliminer ce matériau des possibles candidats matrices inertes sans toutefois le rejeter en tant que matrice de stockage [1].

Perspectives

Des irradiations à fluences plus élevées sont nécessaires pour analyser l'évolution des mécanismes de création de dommages pendant l'irradiation en réacteur, et valider cette simulation par rapport aux irradiations expérimentales dans le réacteur Phénix. Des irradiations à température élevée seraient également utiles pour évaluer la recombinaison des défauts d'irradiation.

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A comparative study of the irradiation effects in high resistivity silicon used in the semiconductor detectors manufacturing.

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As part of the collaboration between the LERMAT Laboratory and the ISTITUTO NAZIONALE di FISICA NUCLEARE (sezione di Milano), preliminary studies of high fluences radiation damage in very high resistivity bulk silicon have been carried out with the intention of understanding the defect formation process. This is very useful to explain the behaviour of detectors, manufactured from this material, which will be used in new generation accelerators (LHC, SSC).

Systematic irradiations of high resistivity silicon and detectors, with heavy ions from GANIL, swift neutrons and energetic electrons allow us to point out very important modifications in the material properties after high dose irradiation. Hall effect measurements carried out on irradiated substrate show that, above a critical fluence which depends on the incident particle, silicon stabilizes in a *near intrinsic* state, whose properties are independent on the incident particle. This state is due to the material compensation by high concentration of radiation induced deep centers. These centers have been identified by Deep Level Transient Spectroscopy and Photoluminescence measurements: they are vacancy-related complex defects (vacancy-oxygen, vacancy-phosphorus, divacancy,...). By fitting the experimental Hall measurements, we have estimated the concentrations of the various defects created by the irradiations.

The substrate modifications induce an alteration of the irradiated electronic devices properties. The $I(V)$ and $C(V)$ characteristics show that at low fluences the saturation value of the leak current of the detectors increases linearly with the fluence. On the other hand, above a threshold fluence, the detector characteristics are deeply altered and it is no more possible to consider the device as an abrupt junction.

The comparison of the results obtained with the different types of particles show that the inelastic energy loss cannot explain the observed differences, which cannot either be taken into account with the total elastic displacement cross-section. Indeed, crucial parameters are also the spatial distribution of defects and the mean nuclear energy deposited into the cascades.

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Vortex pinning by columnar defects in high- T_c superconductors

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Irradiation of superconducting cuprates by swift heavy ions, e.g. 6 GeV-Pb ions, can lead to the creation of columnar defects (CDs) consisting of continuous, amorphous latent tracks with a core diameter of order 100 Å. These CDs can act as very efficient pinning centers for the vortices, and yield huge improvements of transport properties.

During the period 1996-1997, we carried on the study of various pinning parameters by magnetic measurements, and we began to perform transport measurements. We essentially used single crystals of two compounds: $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_8$ (Bi-2212) which has a very large electronic anisotropy between the c axis and the ab planes, and the much less anisotropic $\text{YBa}_2\text{Cu}_3\text{O}_7$ (YBCO). These crystals have a plate-like shape, with the shortest dimension along the c axis.

The electrical resistance has been studied in a Bi-2212 crystal irradiated at $\theta_i = +45^\circ$, as a function of the angle θ between the field and c [1]. We observed a pronounced dip in the $R(\theta)$ curves at $\theta = +\theta_i$ (and not for $\theta = -\theta_i$), demonstrating that, even for a very anisotropic compound in the reversible regime, the presence of CDs is able to induce a vortex line behavior. The magnetic studies were carried out with $H//c$. The persistent current densities J were derived from hysteresis loops. CDs of different mean radius R have been introduced along c in Bi-2212 crystals, by using various experimental conditions (e.g. $R \approx 45$ Å for 6 GeV Pb ions, whereas $R \approx 65$ Å for 0.9 GeV Pb ions). It was found that the J values increase with R in the whole range of field and temperature [2]. This demonstrates that the theoretically expected increase of the pinning energy with R directly affects a macroscopic quantity like J . Another way to vary the effective defect size in the ab planes consists in tilting the ion beam with respect to c . Fig. 1 illustrates the occurrence of a regime where the pinning efficiency (still with $H//c$) is larger for highly angled tracks ($\theta_i = 75^\circ$) than for tracks parallel to c [3]. A further pinning improvement related to entanglement effects can be induced by a dispersion in track directions (splay). The occurrence of such a splay effect in very anisotropic is still very controversial. Various configurations of tracks have been compared in Bi-2212 and did not provide any evidence for a splay effect [4]. This could be due to the low vortex cutting barriers associated to high anisotropy. In YBCO, for which the existence of splay effects is well established, we have studied the influence of various parameters: value of θ_i in bimodal distribution $\pm \theta_i$ around c ; number of directions at a fixed θ_i value; cone-like distributions etc... Several results have been obtained, allowing for a better knowledge of the active processes in a splay. For instance, it was found that the number of track directions (2, 3 or ∞) at a fixed θ_i value (10°) has no effect on the pinning efficiency (Fig. 2).

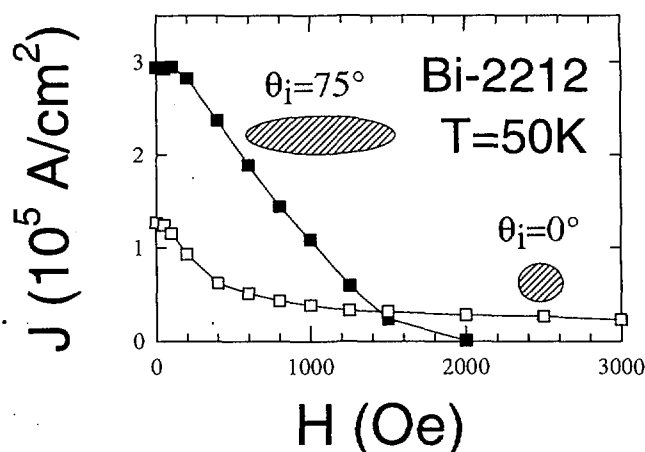


Fig. 1 : Persistent current density vs magnetic field (applied along c), in crystals irradiated by $5 \cdot 10^{10}$ Pb/cm² at an angle θ_i from c .

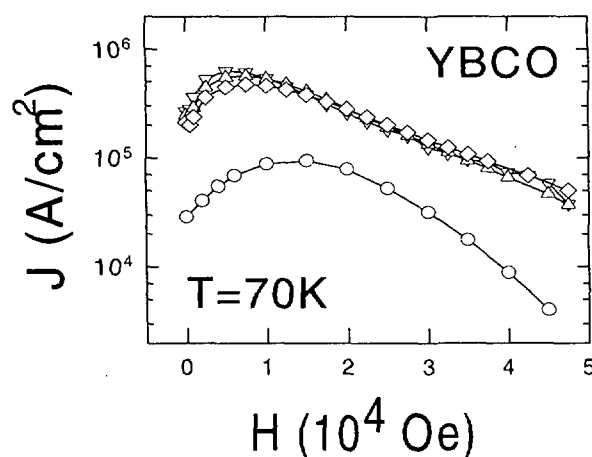


Fig.2 : Persistent current density vs magnetic field (applied along c), in a virgin sample (\circ) and samples irradiated by 10^{11} Pb/cm² along 2 (\triangle), 3 (∇) or ∞ (\diamond) directions inclined of 10° from c .

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